THESIS

Effects of a Wildfire and Salvage Logging on Site Conditions and Hillslope Sediment Production: Placer County, California

Submitted by

Eric Hafen Chase

Department of Forest, Rangeland, and Watershed Stewardship

In partial fulfillment of the requirements

for the Degree of Master of Science

Colorado State University

Fort Collins, Colorado

Spring 2006

COLORADO STATE UNIVERSITY

December 14, 2005

WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION BY ERIC HAFEN CHASE ENTITLED EFFECTS OF A WILDFIRE AND SALVAGE LOGGING ON HILLSLOPE SEDIMENT PRODUCTION: PLACER COUNTY, CALIFORNIA BE ACCEPTED AS FULLFILING IN PART REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

Committee on Graduate work

Greg L. Butters

John D. Stednick

Lee H. MacDonald, Adviser

N. Thompson Hobbs, Department Head

ABSTRACT OF THESIS

EFFECTS OF A WILDFIRE AND SALVAGE LOGGING ON HILLSLOPE SEDIMENT PRODUCTION: PLACER COUNTY, CALIFORNIA

Post-fire sediment production rates have been measured in many areas, but there are few published data on how salvage logging affects post-fire sediment production. The primary objective of this study was to compare sediment production rates from sites burned at high severity and subjected to helicopter, cable, or tractor logging. The study sites were in the Star fire, which burned 7,080 ha in the central Sierra Nevada of California in late summer 2001. Sediment production was measured with sediment fences on 32 burned sites and five unburned sites over the 2002-2003 and 2003-2004 wet seasons. The independent variables measured on each site included slope, aspect, contributing area, percent bare soil, percent rocky outcrop, percent ground disturbance, soil texture, and soil water repellency. Soil compaction and bulk density were measured on a subset of sites.

The first wet season had a calculated rainfall erosivity of 556 MJ mm ha^{-1} h^{-1}. Mean sediment production rates were 2.6 Mg ha^{-1} from the burned, logged sites and 0 Mg ha^{-1} from the unburned sites. The second wet season had only 21 MJ mm ha^{-1} h^{-1} of erosivity because most of the precipitation fell as snow, and the burned and logged sites had a mean sediment production rate of 0.11 Mg ha^{-1}.

Mean sediment production rates did not significantly differ by logging treatment due to the high variability between sites and the very low sediment production rates in the second wet season. Mean percent bare soil declined from 37% in summer 2002 to 21%

in summer 2004, and percent bare soil was the most important univariate control on sediment production in the first wet season. The cable- and tractor-logged sites had significantly more ground disturbance than the sites logged by helicopter ($p<0.001$). In the first wet season there was a significant relationship between percent disturbance and sediment production for the nine cable-logged sites (R^2=0.47; p=0.042).

Multivariate modeling showed that sediment production was a function of the contributing area, percent bare soil, percent area with litter <1 cm thick, rainfall erosivity, soil water repellency at the soil surface, and soil texture (R^2=0.76). The model tended to over-predict low values of sediment production and under-predict high values.

The results suggest that post-fire salvage logging treatments that increase ground disturbance and bare soil will generate more sediment, but statistically significant differences in sediment production may be difficult to detect given the variability between sites and in logging practices.

Eric Hafen Chase
Department of Forest, Rangeland, and Watershed Stewardship
Colorado State University
Fort Collins, CO 80523
Spring 2006

ACKNOWLEDGEMENTS

This study would not have been possible without the cooperation and support of the Eldorado National Forest. I am especially grateful to Chuck Mitchell and Tom Kohler for their commitment to the project and for providing access to the study site, vehicles, volunteer help, and housing. I am also grateful to the Placer County Water Agency for their support of the project and I would like to acknowledge Marie Davis for her work as the liaison between PCWA and the Eldorado National Forest.

I would like to express my gratitude to my advisor Dr. Lee H. MacDonald for providing me the opportunity to work on this project. I have learned many invaluable lessons from Lee and am grateful for his support and guidance during this ever-evolving project. I thank my other committee members, Dr. John Stednick and Dr. Greg Butters, for their encouragement and thoughtful reviews of my research.

Many thanks go to Jeremy Shaw, Cherie Westbrook, Jay Pietraszak, Daniella Rough, Darren Hughes, and Ethan Brown for their great ideas, insights and reviews of my work. Without their support and knowledge this thesis would not have been possible. I am indebted to both Ben Snyder and Dan Woolley for their help in the field and in the laboratory. I thank James Donaldson for his help during the first summer that allowed me to arrive in Colorado in time for classes. I also thank all of the people from the Eldorado National Forest who volunteered their time to help with the project. Finally, I thank my wife Kimberly Johnson for her encouragement, love, and support over the past three years, as this has been vital to my success at Colorado State University.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

Fire suppression has altered natural fire regimes in many forested areas in the western United States (Agee, 1996). Long-term data suggest that the advent of fire suppression in the early 1900s initially decreased the area burned in the western United States, but the total area burned appears to have increased since the early 1980s (Agee, 1993). In the mixed conifer forests of the Sierra Nevada, the increased fuel loading due to fire suppression has increased the intensity and size of wildfires relative to pre-suppression conditions (SNEP, 1996a).

High severity wildfires are a concern because they can increase runoff and erosion rates by one or more orders of magnitude relative to unburned forest and shrub lands (Campbell et al., 1977; Helvey, 1980; Robichaud et al., 2000; Moody and Martin, 2001; MacDonald et al., 2004). The sediment delivered to streams after wildfires can increase sedimentation in downstream areas, reduce channel capacity, and degrade municipal water supplies (Moody and Martin, 2001). The increased delivery of sediment to streams can adversely affect aquatic organisms and their habitat (Rinne, 1996).

The increase in runoff and sediment production after wildfires can be attributed to several factors. In coniferous forests and certain other vegetation types, such as chaparral, the volatilization of organic compounds from the litter and soil can result in a water repellent layer at or near the soil surface (DeBano, 2000). The net effect of this water repellent layer is to decrease infiltration rates and cause a shift in runoff processes from subsurface storm flow to overland flow (DeBano, 1998; Ice et al., 2004). The loss of the litter layer can further reduce infiltration rates through rainsplash erosion and soil sealing (Inbar et al., 1998; DeBano, 2000). Increases in runoff after wildfires also have been attributed to increased saturation overland flow due to decreased transpiration from the loss of vegetation (Mackay and Cornish, 1982). Soil water repellency and the loss of the protective litter layer are considered to be the most important factors in generating overland flow and the large increases in runoff and sediment production after wildfires (DeBano 2000; Benavides-Solorio, 2003).

The increase in surface runoff increases the local shear stress and this can lead to channel initiation in formerly unchannelled swales as well as incision in pre-existing lower-order channels. Rilling, gullying, and channel incision are important sources of sediment and have been shown to be the dominant mechanisms for generating and delivering sediment to stream channels (Robichaud, 2000; Moody and Martin, 2001). Montgomery and Dietrich (1994) found that channel initiation was controlled primarily by the product of slope and contributing area.

While post-fire sediment production rates have been measured in many areas (Robichaud et al., 2000), there are few data on sediment production rates after wildfires in the mixed conifer forests of the Sierra Nevada. Three sediment fences on study sites burned at high severity in the Tahoe National Forest yielded first-year sediment production rates of 2.2 Mg ha^{-1} to 15.5 Mg ha^{-1} (MacDonald et al., 2004). In the second year after burning, sediment production rates declined by almost an order of magnitude. This decline can be attributed to the lower rainfall erosivity in the second year as well as the increase in ground cover and presumed reduction in soil water repellency. In the Eldorado National Forest (ENF), study sites burned at low and moderate severity have generally produced very little sediment (MacDonald et al. 2004), and this is consistent with other studies from different regions (e.g., Robichaud and Waldrop, 1994; Benavides-Solorio, 2003).

Post-fire salvage logging in the western United States has increased in recent years (McIver and Starr, 2000). The decision to salvage log after a wildfire is a controversial issue and little information exists on how post-fire logging affects sediment production rates (McIver and Star, 2000; McIver and Star, 2001).

The limited data on post-fire salvage logging indicate that tractor and cable logging significantly increase percent ground disturbance compared to burned and unlogged sites. The effect of different salvage logging treatments on percent ground disturbance was studied on the 1970 Entiat fire in the ponderosa pine and Douglas fir forests of Washington (Klock, 1975). The mean percent disturbance for tractor skidding over bare ground was 36%, followed by 10% for tractor skidding over snow, 32% for cable logging without full suspension, 2.8% for cable logging with full suspension, and less than 1% for helicopter logging (Klock, 1975). Percent ground disturbance also was measured after salvage logging on the 1987 Stanislaus National Forest fire in the central Sierra Nevada mountains in California (Chou et al., 1994a, b). The mean percent disturbance for tractor logging was 35% versus 18% for the cable-logged sites.

Another possible effect of salvage logging is soil compaction, which can lead to lower infiltration rates and increased overland flow (SNEP, 1996b; Beschta et al., 2004). Ground-based salvage logging is more likely to induce soil compaction than cable or helicopter logging (McIver and Star, 2000; Beschta et al., 2004). However, there are no published data on compaction rates from salvage logging.

Some studies have argued that salvage logging may reduce post-fire sediment production by breaking up soil water repellency and increasing infiltration rates by disturbing sealed soil surfaces (Bautista et al., 1996). Additionally, slash from salvage logging can increase percent cover and surface roughness, thereby reducing overland flow velocities and surface erosion (Shakesby et al., 1996; Kuehn, 2001; Poff, 2002).

In the first year after the 1970 Entiat fire, the mean sediment production rate was approximately 0.2 Mg ha^{-1} for burned and logged watersheds. This was approximately half of the rate from the unlogged watershed (Helvey, 1980). In the second year after burning, the sediment production rate for burned and logged watersheds increased to 1.6 Mg ha^{-1}, and again this value was half of the rate from the unlogged watershed (Helvey, 1980).

Sediment production was measured for three years after salvage logging on the Stanislaus fire in the central Sierra Nevada (Chou et al., 1994a, b). Mean sediment production from the tractor-logged sites was approximately 5 Mg ha^{-1}, or 30% less than the mean value from the unlogged sites. Sediment production from the cable-logged sites was approximately 4 Mg ha^{-1}, or 40% less than the value from unlogged sites. The differences in sediment production between logged and unlogged sites were not statistically significant (Chou et al., 1994a, b).

A study in Australia using rainfall simulators showed that logging after wildfire increased sediment production. For a simulated 10-year rainfall event, sediment production from burned and logged plots was 1.1 Mg ha^{-1} as compared to 0.05 Mg ha^{-1} from burned and unlogged plots (Wilson, 1999).

These studies show that salvage logging may increase or decrease post-fire erosion rates relative to burned and unlogged areas. These studies also indicate that tractor logging is likely to cause more ground disturbance and erosion than cable or helicopter logging. They also identify some potential problems in trying to determine the effects of salvage logging on sediment production, such as the variability between years and between sites. Even less information is available on how different logging practices affect the factors that control post-fire sediment production

1.1. Goals and objectives

The primary goal of this study was to compare sediment production rates from different post-fire logging practices on sites that had burned at high severity. Sediment production rates were measured at 37 sites over the 2002-2003 and 2003-2004 winter wet seasons. The secondary goals were to evaluate the potential role of factors such as percent ground cover, soil disturbance, and site conditions on sediment production (Table 1), and to develop empirical models for predicting sediment production from sites subjected to salvage logging.

The specific objectives of this study were to: 1) compare hillslope-scale sediment production rates from burned and unlogged sites to burned sites subjected to tractor, cable, or helicopter logging, respectively; 2) assess the effect of different site factors on sediment production rates; 3) compare the effect of different salvage logging practices on key site factors; 4) measure sediment production from rill and interrill erosion, and compare these values to the total sediment collected in the sediment fences; and 5) develop empirical models for predicting sediment production from burned and salvage-logged hillslopes in the central Sierra Nevada.

Dependent variable	Independent variable
Sediment production	Fire severity
	Percent ground cover
	Soil water repellency
	Hillslope gradient
	Contributing area
	Percent mechanical disturbance
	Aspect
	Vegetation type
	Soil texture
	Annual precipitation
	Max. 30-minute rainfall intensity
	Annual rainfall erosivity

Table 1. List of measured independent variables.

2. STUDY AREA

The study area is the Star wildfire in the central Sierra Nevada in California (Figure 1). The fire began on 25 August 2001 and burned approximately 7,080 hectares (ha) before containment on 13 September 2001. The burned area included 980 ha on the Eldorado National Forest, 4,240 ha on the Tahoe National Forest, and 1,860 ha of private industrial forest land. The study area is of special concern to both public and private land holders because of the high volume of timber and it provides drinking water and hydroelectric power to over one million people in Placer and Sacramento counties.

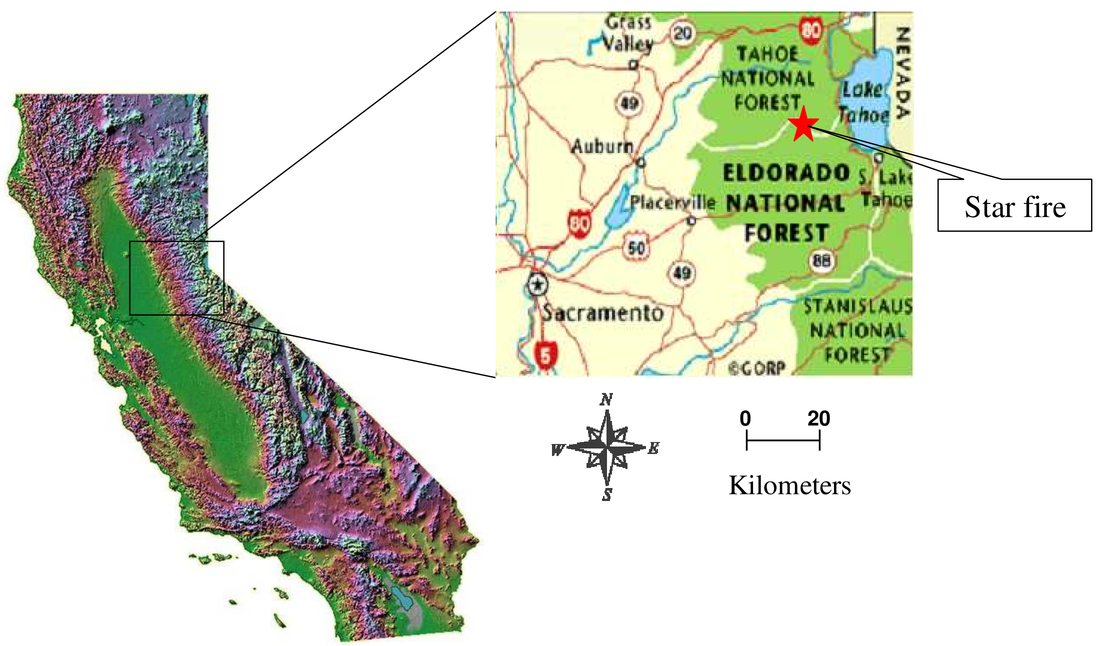

Figure 1. Location of the Star Fire.

Elevations in the study area range from approximately 1,480 to 1,830 meters. The study area has a Mediterranean climate with hot, dry summers and a cold wet season (USDA, 1985). Most of the precipitation falls as snow between 1 November and 30

April (USDA, 1985). The mean annual precipitation is 1,460 mm at an elevation of 1,710 m (Greek Store weather station) and 1,560 mm at an elevation of 1,480 m (Hell Hole weather station). The standard deviations of the annual precipitation at these two sites are 265 mm and 325 mm, respectively.

The main watersheds within the study area include Chipmunk Creek, the North Fork of Long Canyon, and the Middle Fork of the American River (Figure 2). The topography consists of steep, incised valleys running from southwest to northeast with generally flat ridgetops (Figure 2). Streams within the study area are cobble-bedded and bedrock-controlled. Forests at the lower to middle elevations are dominated by canyon live oak (*Quercus chrysolepis*) and mixed conifer forests with ponderosa pine (*Pinus ponderosa)*, sugar pine (*Pinus strobes*), incense cedar (*Calocedrus decurrens*), and abundant white fir (*Abies concolor*). Red fir (*Abies magnifica*), Jeffrey pine (*Pinus jeffreyi*), and lodgepole pine (*Pinus contorta var. murrayana*) are dominant at higher elevations (USDA, 1985). Ground vegetation consists of mostly greenleaf manzanita (*Arctostaphylos patula*), deerbrush (*Ceanothus integerrimus*), snowbrush (*Ceanothus velutinus*), mountain whitethorn (*Ceanothus cordulatus*), and bear clover (*Chamaebatia foliolosa*) (USDA, 1985).

The geology of the study area is dominated by an andesitic lahar (Mehrten formation) of the late Eocene period (USDA, 1985). Subsequent glaciation at the higher elevations left behind glacial till and outwash sediments in the southwest portion of the study area. Soils derived from the andesitic parent material include the Cohasset, McCarthy, Ledmount, and Waca soil series (USDA, 1985). All of these soils are sandy loams that often contain greater than 30% gravel and cobbles. The Zeibright soil series is a gravelly coarse-textured loam formed on the granitic glacial till and outwash sediments. All of the soils are characterized by moderate permeability (5-15 cm hr^{-1}) in the upper 15 cm (USDA, 1985).

On the private timberlands both tractor and cable logging began during fall 2001; these operations were completed by fall 2002. On public lands managed by the U.S. Forest Service, salvage logging began in fall 2002; by summer 2004 approximately 210 ha were tractor-logged and 152 ha were helicopter- or cable-logged.

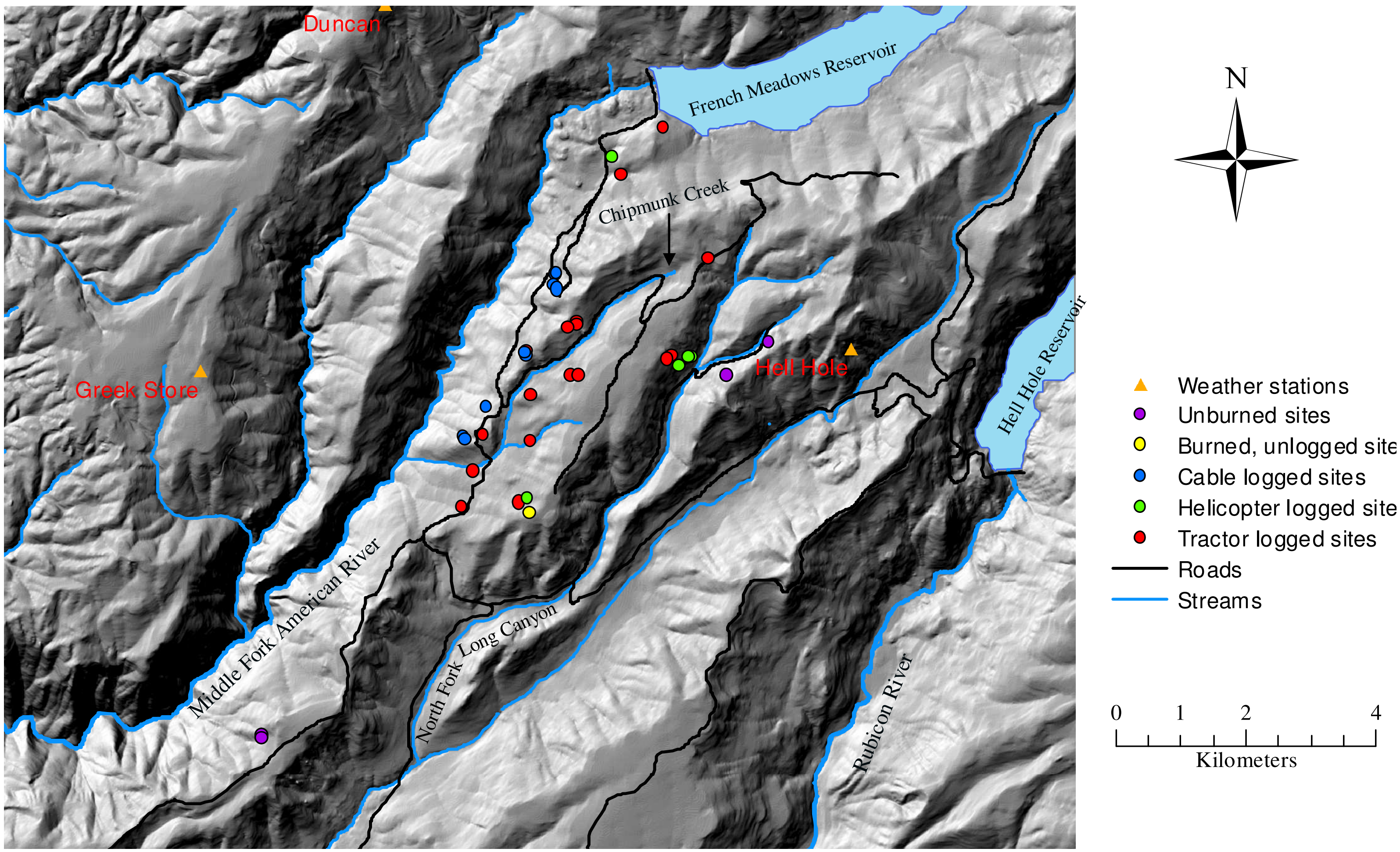

Figure 2. Location of study sites and nearby weather stations.

3. STUDY DESIGN

Since the two primary private landowners (Sierra Pacific Industries and Lone Star) provided access to their lands, the Star fire offered a relatively unique opportunity to compare post-fire sediment production rates resulting from different types of salvage logging in the central Sierra Nevada. There was one wet season between the fire in fall 2001 and the establishment of the study sites in summer 2002. In this thesis, the first wet season refers to the 2002-2003 wet season, and the second wet season refers to the 2003-2004 wet season. Study sites were zero-order basins or the uppermost portions of first-order basins that had convergent topography where a sediment fence could be installed.

The initial study design in summer 2002 consisted of 32 burned sites and 5 unburned sites (Table 2). Three of the unburned study sites were less than 2 km east of the study area and the other two unburned study sites were approximately 4 km southwest of the study area (Figure 2). The burned sites were stratified into 16 burned sites on private lands that had been subjected to salvage logging, and 16 burned sites (12 sites on public lands and 4 sites on private lands) that had not been salvage logged. These two groups were further separated into sites with slopes greater than 35%, where cable or helicopter logging would normally be applied, and sites with less than 35% slope, where tractor logging would normally be applied. Hence the 32 burned sites represented four treatments with 8 replicates of each treatment: 1) steep (>35% slope), burned and unlogged sites suitable for cable or helicopter logging; 2) flatter (<35% slope), burned and unlogged sites suitable for tractor logging; 3) steep burned sites that had been salvage-logged using cables; and 4) flatter burned sites that had been salvage-logged using tractors (Table 2). There were no helicopter-logged sites when the study sites were established in summer 2002. Elevations of the burned and unburned study sites ranged from 1,480 to 1,830 m. All of the burned sites were within 7 km of each other (Figure 2).

Treatments	Number of Sites		
	Summer 2002	2002-2003 wet season	2003-2004 wet season
Unburned	5	5	5
Burned and unlogged tractor-suitable	8	2	1
Burned and salvage-logged using tractors	8	16	17
Burned and unlogged cable- or helicopter-suitable	8	1	0
Burned and salvage-logged using cables	8	9	9
Burned and salvage-logged using helicopters	0	4	5

Table 2. Sample sizes of each logging treatment over time.

In fall 2002, the Eldorado NF completed an Environmental Impact Statement (EIS) for salvage logging (USDA, 2002). Logging began almost immediately, and 10 of the 12 sites on public lands that were to be left as burned and unlogged controls were logged before the first wet season. Additionally, 3 of the 4 sites on private lands that were to be left as burned and unlogged controls were tractor-logged before the first wet season. Hence, the stratification of study sites for the first wet season included: 5 unburned sites; 9 burned sites that were salvage-logged using cables; 4 burned sites that were salvage-logged using helicopters; 16 burned sites that were salvage-logged using tractors; and 3 burned and unlogged sites (Table 2). The sediment fence on one of the four helicopter-logged sites (CR-West-2) was damaged by logging in fall 2002, so no sediment production data were collected during the first wet season for that site.

Efforts in summer 2003 to find new sites that were burned at high severity but unlogged were unsuccessful. Of the three remaining burned and unlogged sites, one was tractor-logged and one was helicopter-logged immediately prior to the second wet season

(Table 2). All 5 helicopter-logged sites were on lands managed by the U.S. Forest Service, while 7 of the 9 cable-logged sites and 12 of the 17 tractor-logged sites were on private lands (Table 3).

To minimize the variability within logging treatments, all of the study sites were on volcanic soils as mapped by the Eldorado National Forest Soil Survey (USDA, 1985). All of the burned study sites were in areas that had burned at high severity, and in forests dominated by white fir. None of the sites were mechanically ripped (subsoiled) prior to tree planting except for the upper one-third of the contributing area of site CR-1-North.

3.1. Logging practices

In this study, tractor logging refers to the use of wheeled or tracked vehicles to transport logs from the stump to a collection point (landing). Cable logging transports logs from the stump to the landing by means of aerial cables. On the Star fire, the logs were only partially suspended, so cable rows were created as the ends of the logs were dragged across the ground. In helicopter logging, the logs are lifted off the ground and fully suspended by a cable attached to the helicopter. Tractor logging generally causes the most site disturbance, followed by cable and then helicopter logging (Klock, 1975) (Figures 3, 4). Logging was carried out by private contractors on both public and private lands. On lands managed by the U.S. Forest Service, private contractors followed best management practices set out in the EIS (USDA, 2002). On private lands, the contractors followed a similar set of best management practices as specified by the California Department of Forestry (CDF, 2002).

Site	Logging treatment	Year logged	Land ownership	Contributing area (ha)	Axis slope (%)	Aspect
CR-17N12YL-1	Cable	2002	Private	0.59	37	NW
MF-1	Cable	2002	Public	0.14	44	N
MF-1-South	Cable	2002	Private	0.04	23	N
MF-2	Cable	2002	Public	0.09	46	N
MF-2-South	Cable	2002	Private	0.03	39	N
MF-3	Cable	2002	Private	0.43	48	NW
MF-3-South	Cable	2001	Private	0.05	58	NE
MF-4	Cable	2002	Private	0.08	53	N
MF-4-South	Cable	2001	Private	0.09	53	N
Mean				**0.17**	**45**	
Standard deviation				**0.20**	**11**	
CR-West-2	Helicopter	2002	Public	0.04	32	W
FM-1	Helicopter	2003	Public	0.06	49	N
LC-1-North	Helicopter	2002	Public	0.38	43	SW
LC-2-North	Helicopter	2002	Public	0.56	41	SW
LC-3-North	Helicopter	2002	Public	0.49	36	SW
Mean				**0.31**	**40**	
Standard deviation				**0.25**	**7**	
CR-1-NE	Tractor	2001	Private	0.18	13	S
CR-1-North	Tractor	2001	Private	0.39	22	NW
CR-2-North	Tractor	2002	Private	0.30	27	NW
CR-5-North	Tractor	2002	Public	0.01	22	SW
CR-7-North	Tractor	2001	Private	0.04	25	SW
CR-Creek-1	Tractor	2001	Private	0.99	20	SW
CR-Creek-2	Tractor	2001	Private	1.70	20	SW
CR-Creek-3	Tractor	2002	Private	0.15	18	SW
CR-West-3	Tractor	2002	Private	0.51	33	N
FM-3	Tractor	2001	Public	0.18	23	NE
FM-4	Tractor	2003	Public	0.13	21	NE
LC-5-North	Tractor	2002	Public	0.38	35	S
LC-6-North	Tractor	2002	Public	0.46	35	S
MF-6-South	Tractor	2001	Private	0.06	35	N
MF-7-South	Tractor	2001	Private	0.59	20	W
MF-8-South	Tractor	2001	Private	0.14	25	NW
MF-9-South	Tractor	2001	Private	0.18	28	N
Mean				**0.38**	**25**	
Standard deviation				**0.42**	**7**	
CR-West-1	Unlogged	--	Private	0.12	35	N
HH-1	Unburned	--	Public	0.08	36	SE
LC-1-South	Unburned	--	Private	0.36	36	N
LC-2-South	Unburned	--	Private	0.69	36	N
RR-1-North	Unburned	--	Public	0.94	41	W
RR-2-North	Unburned	--	Public	0.82	48	W
Mean				**0.58**	**39**	
Standard deviation				**0.35**	**5**	

Table 3. Study sites by logging treatment with year logged, land ownership, contributing area, slope, and aspect.

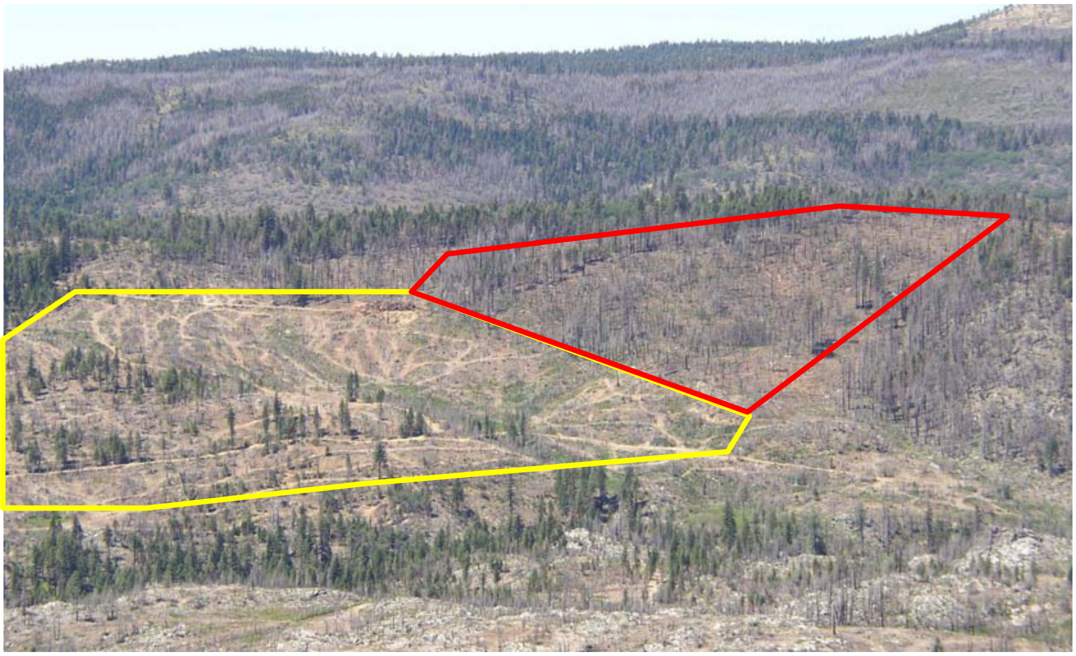

Figure 3. Photo of tractor-logged area (yellow polygon) and helicopter-logged area (red polygon) on the Star Fire. Note the different amounts of ground disturbance and roads between the two logging treatments.

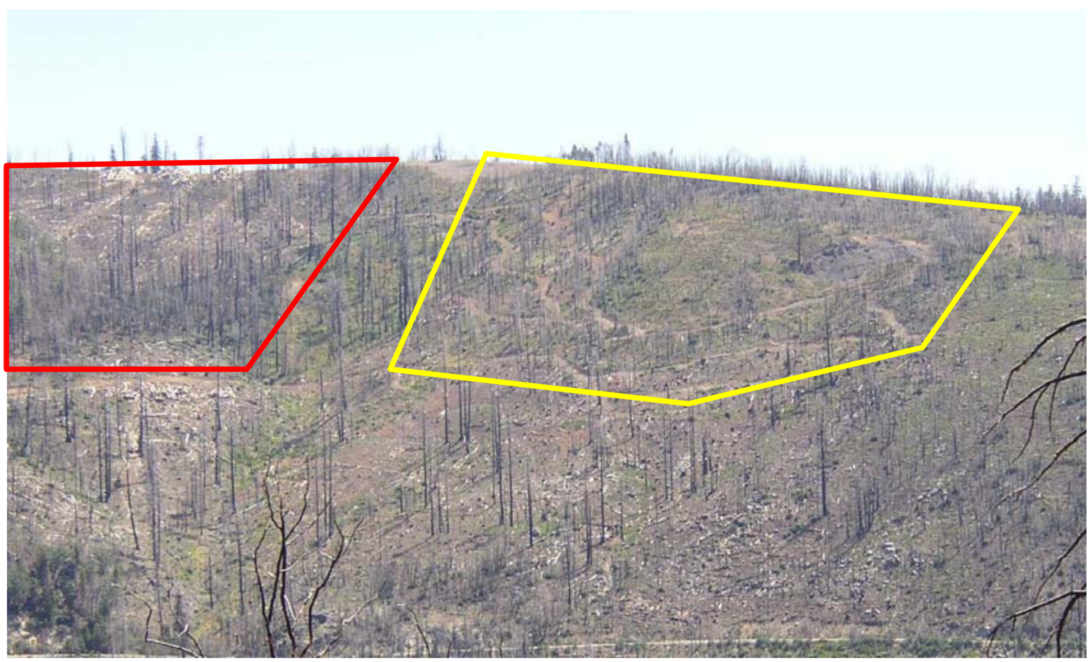

Figure 4. Photo of tractor-logged area (yellow polygon) and cable-logged area (red polygon) on the Star Fire. Note the different amounts of ground disturbance and roads between the two logging treatments.

4. METHODS

4.1. Sediment production

Hillslope sediment production rates were measured with sediment fences in zero-order or the uppermost portions of first-order basins (Figure 5). The sediment fences were constructed from 1.2-m wide geotextile fabric and 1.3-cm steel rebar (Figure 5) (Robichaud and Brown, 2002; Benavides-Solorio, 2003; Libohova, 2004). The upslope edge of each fence was secured to the ground surface with landscape staples or rocks. In front of each fence a layer of fabric was placed on the ground surface to separate the sediment trapped behind the fence from the underlying soil. This "apron" also facilitated the removal of the trapped sediment.

Figure 5. Typical sediment fence and crest gauge with a second fence installed to increase the sediment storage capacity. Picture taken in summer 2003 in a site that was tractor-logged in fall 2001.

The upslope ends of each fence were higher than the middle to maximize the trapping efficiency and to ensure that excess water would flow over the fence rather than around the edges. Because the study sites were inaccessible during the winter, multiple fences were installed on most study sites to increase the storage capacity (Figure 5). After spring snowmelt, the accumulated sediment was manually removed in 20-liter buckets and weighed in the field to the nearest 0.5 kilogram. After weighing, the sediment was placed on a tarp and thoroughly mixed. Two samples of approximately 500 g each were taken, placed into Ziploc® bags, labeled with a permanent maker, and stored in a cool, dry place. At the end of each summer, the samples were dried at Colorado State University to determine the gravimetric water content (Gardner, 1986). The measured water contents were used to convert the field-measured wet weights to a dry mass. The calculated dry mass was divided by the contributing area to obtain sediment production per unit area.

4.2. Measurement of independent variables

The amount and intensity of precipitation was obtained from three weather stations: (1) Hell Hole, which is approximately 4 km east of the center of the study area at an elevation of 1,480 m; (2) Greek Store, which is approximately 6 km west of the center of the study area at an elevation of 1,710 m; and (3) Duncan Lookout, which is approximately 6 km north and slightly west of the center of the study area at an elevation of 2,165 m (Figure 2). The resolution of each gauge was 0.25 mm. The Hell Hole gauge was used to represent the entire study area because the wet season precipitation is derived from large frontal storms (Amorocho and Wu, 1977), and this gauge was closest to most of the study sites (Figure 2). Snow water equivalent (SWE) data from the Greek Store weather station were used to determine the timing of the snow cover. All data were obtained from the California Data Exchange Center (http://cdec.water.ca.gov). Long-term precipitation data from the Hell Hole and Greek Store stations were used to determine the representativeness of the 2002-2003 and 2003-2004 wet seasons.

For each wet season, the maximum storm erosivity and annual storm erosivity was calculated from the one-hour rainfall data. Since snowfall has minimal erosive energy (Cooley et al., 1988), erosivity was calculated only for the snow-free period. Individual storms were defined as precipitation events separated from each other by at least 6 hours (Mutchler et al., 1994). The kinetic energy of each rainfall event was calculated by:

$$E = [0.29\ (1-0.72^{(-0.05i)})] \times d \qquad (1)$$

where E is the kinetic energy in MJ ha^{-1}, i is the rainfall intensity in mm h^{-1}, and d is the rainfall depth in mm (Brown and Foster, 1987).

Annual erosivity was calculated by:

$$E_A = \sum E\ I_{30} \qquad (2)$$

where E_A is the annual rainfall erosivity in MJ mm ha^{-1} h^{-1}, e is the kinetic energy per storm, and I_{30} is the maximum 30-minute rainfall intensity for each storm in mm h^{-1} (Renard et al., 1997). Annual sediment production was normalized by the annual erosivity to facilitate comparisons between years.

Crest gauges were installed in the swale axis at each site in summer 2002 to determine the depth of flow (Figure 5) (Buchanan and Somers, 1968). The crest gauges were constructed of 5-cm diameter PVC pipe with three intake holes aligned vertically starting at the bottom of the gauge. The gauge was placed flush with the mineral soil surface and held in place with rebar. Granulated cork was placed in the bottom of the gauge along with a graduated wooden dowel. The maximum height of the granulated cork on the dowel was recorded after each wet season.

The contributing areas for all but three sites were determined with a Trimble Pathfinder XRS global positioning system (GPS) with sub-meter accuracy. For three of the unburned sites, the contributing areas had to be estimated from linear transects because the canopy was too thick to use the GPS. Burn severity was assessed following criteria developed by Wells et al. (1979) and the U.S. Forest Service (1995). Aspect was measured in the axis at the midpoint of each site with a compass adjusted for local declination. Axis gradients were measured with a clinometer.

Within each contributing area, three soil samples of at least 250 g each were collected from the soil surface (0-5 cm). Sample locations were chosen at random. The samples were aggregated, dried for 24 hours at 100° C to determine dry mass, and burned for 8 hours at 400° C to remove organic matter (Ben-Dor and Banin, 1989). The particle-size distribution of each composite sample was determined by using sieves with screen openings of 19, 12.7, 6.3, 4.75, 3.35, 2, 1.68, 1, 0.425, 0.25, 0.15, and 0.075 mm. These screen openings in mm correspond to -4.25, -3.67, -2.67, -2.25, -1.75, -1.00, -0.75, 0.00, 1.25, 2.00, 2.75, and 3.75 phi units (Grender, 1961). Each fraction was weighed and the cumulative particle-size distribution was used to determine the size of the 16th, 50th and 84th percentiles (D_{16}, D_{50}, and D_{84}, respectively). The D_{16} and D_{84} represent one standard deviation from the median particle size (D_{50}) (Bunte and Apt, 2001).

Percent cover within each study site was determined in mid-summer in 2002, 2003, and 2004 using a point-count method similar to Parker (1951). The length of each study site was measured with a flexible tape, and 3 to 5 equally-spaced horizontal transects were established, depending on the size of the contributing area. A second tape was placed along each transect to the edges of the contributing area, and the surface cover was classified along the tape at equally-spaced points starting from a randomly selected origin. Ten surface cover classes were used: bare soil, litter <1 cm thick, litter >1 cm thick, live vegetation, rock fragment >2 cm, rock outcrop, small woody debris (<5 cm diameter), large woody debris (>5 cm diameter), standing tree, and stump. The number of sample points per site ranged from 93 to 222.

Percent mechanical disturbance was measured in summer 2003 using five linear transects within each contributing area. Three transects were placed laterally across the contributing area and one transect was placed longitudinally on each side of the swale axis. Mechanical disturbance was defined as any soil movement or disruption due to logging. Percent disturbance was determined from the summed length of disturbed soil over the total length of the five transects. Percent disturbance was remeasured in summer 2004 in study sites FM-1 and FM-4, as these sites were disturbed by salvage logging in fall 2003 (Table 3).

Soil water repellency was determined in summer 2002, 2003 and 2004 by measuring the critical surface tension (CST) (Wallis and Horne, 1992; Huffman et al., 2001) at three randomly-selected, undisturbed locations within the contributing area of each site. At each location, two pits approximately 30 cm apart were sampled. Any loose ash and litter were swept aside and the CST was measured at 2.5-cm increments from the mineral soil surface (0 cm) to a depth of 12.5 cm. Five drops of deionized water were applied at each depth. If four of the five drops were not absorbed within 5 seconds, drops with a successively greater concentration of ethanol were applied (Watson and Letey, 1970). The solutions used had 0, 1, 3, 5, 9, 14, 19, 24, 34, 48, 60, and 80% concentrations of ethanol by volume. Increasing concentrations of ethanol decrease the surface tension; the CST value is the surface tension at which the drops are readily absorbed into the soil. Hence, lower CST values represent stronger soil water repellency. CST measurements were made in July because the soils were quite dry, and soil moisture can decrease or eliminate soil water repellency (MacDonald and Huffman, 2004). The CST values from the six pits were averaged to obtain a single value for each depth at each study site.

Soil water repellency also was measured at two pits in each of 12 sampling locations on cable rows and 12 sampling locations on skid trails. The CST values from the two pits were averaged to obtain a single value for each depth at each sampling location.

4.3. Compaction measurements

The compaction due to logging was determined by comparing pocket penetrometer data from skid trails and cable rows to adjacent undisturbed areas (Amacher and O'Neill, 2004). A penetrometer measures the unconfined compressive strength of soils, which is a surrogate for compaction. Twenty paired measurements were made along one skid trail in 10 different sites in summer 2003 (n=200 pairs), and on each of two cable rows in three different sites in summer 2004 (n=120 pairs). The precise locations were randomly chosen along the total length of the skid trail or cable row. Each reading was recorded to the nearest 0.25 kilogram per square centimeter. Pairwise comparisons were made between disturbed and undisturbed areas for each site, and for the overall mean disturbed and undisturbed values from the skid trails and the cable rows, respectively. A soft soil adapter was used when the soil did not provide enough resistance for the initial reading.

4.4. Rill, erosion pin, and bulk density measurements

In summer 2003, rill and interrill erosion measurements were added in an attempt to better understand the underlying erosion processes. Bulk density and rill density measurements were added in summer 2004. For this study, rills were defined as channels at least 5 cm deep.

Rill erosion was assessed by measuring the cross-sectional area of the primary rill in the swale axis in five study sites in summer 2003 and again in summer 2004. Two cross-sections per rill were established in three tractor-logged sites and one cable-logged site, while in one tractor-logged site there was only one cross-section. Rill cross-sections were measured with a 1-m long aluminum pin-frame with a pin spacing of 2.0 cm. The frame was placed on permanent steel rods, and the vertical distance from the bottom of the pin frame to the ground surface was measured for each pin. The lower cross-section was assumed to represent the length from the fence to the midpoint between the cross-sections. The upper cross-section was assumed to represent the distance from the midpoint between the cross-sections to the upper cross-section, and then that same distance beyond the upper cross-section. The change in cross-sectional area from 2003 to 2004 was multiplied by the segment length to obtain the total volume of incision or aggradation. These values were summed for each site, and the total volume was multiplied by the bulk density to obtain a total mass.

In summer 2003 a grid of erosion pins (Hudson, 1993; Sirvent et al., 1997) was installed in the interrill areas on 12 study sites. Nine of the 12 sites were tractor-logged and the remaining three sites were cable-logged. The 12 sites included the 5 sites where rill measurements also were being made. The erosion pins were 25-cm long metal nails 1-cm in diameter with a head diameter of 2.5 cm. In each site, 15 to 30 pins were placed at 3 to 5 m spacings along three linear transects perpendicular to the swale axis. The change in surface elevation at each pin was determined by measuring the distance from the head of each pin to the soil surface in summer 2004. The volume of interill erosion from each study site was assumed to equal the average elevation change times the contributing area. The mass of interrill erosion was calculated by multiplying the eroded volume by the surface bulk density.

Bulk density samples were collected on the 12 study sites where rill and erosion pin measurements were taken. Samples were collected by driving a 5.65-cm diameter by 3.85-cm high sample ring into the soil surface. Two samples were collected on each side of the swale axis at three locations within each contributing area for a total of 6 samples per site. The samples were oven dried, weighed, and averaged to determine a mean bulk density for each site (Blake and Hartge, 1986).

In summer 2004, the length of the rills in each site was measured with a flexible measuring tape. The rill density for each site was calculated by dividing the total rill length by the contributing area.

4.5. Data analysis

During the first wet season, the sediment production value from one site was unusable as the logging activities destroyed the fence. At a second site the sediment fences had failed, probably as a result of the deep snowpack. Hence, the first year's data from these two sites were excluded from the analysis. At two sites, the fences were overtopped by sediment, but these data were included in the analysis of sediment production rates between logging treatments because of the limited sample sizes of the different treatments.

The sediment production data were log transformed prior to the analysis to obtain a normal distribution (Ott and Longnecker, 2001). Analysis of variance (ANOVA) was used to determine if there were significant differences between sediment production rates between logging treatments for each year. Sediment production and sediment production rates were compared between years and logging treatments using t-tests.

Linear regression was used to assess the relationship between each independent variable and sediment production for each wet season. Significant empirical model variables at $p \leq 0.05$ were selected using Mallow's Cp as forward, backward, and stepwise multiple regression results were not consistent (Ott and Longnecker, 2001). The significant empirical model variables identified by Mallow's Cp were used to construct a general linear model (GLM) for predicting sediment production from the salvage-logged sites. Data from the overtopped fences were excluded during the multivariate analysis because the pooled dataset was not size limited (n=56).

The mean CST values for each year at each depth were compared using a repeated measures analysis with the Satterthwaite approximation of the t-statistic (Ott and Longnecker, 2001). The mean CST values for disturbed versus undisturbed sites were compared at each depth using t-tests. Mean percent disturbance was compared between logging treatments and between landowners using t-tests. Similarly, t-tests were used to compare the mean penetrometer values from the disturbed and undisturbed locations from skid trails and cable rows.

Changes in each ground cover class over time were compared using a repeated measures analysis with the Satterthwaite approximation of the t-statistic (Ott and Longnecker, 2001). For each year t-tests were used to compare the mean percent bare soil between logging treatments, and between logged and unlogged sites.

5. RESULTS

5.1. Precipitation

Annual precipitation at Hell Hole was 1,750 mm in the first wet season, or 12% above the long-term mean of 1,560 mm. In the second wet season, the total precipitation was 1,220 mm, or 78% of the long-term mean (Figure 6).

During the first wet season, four rainfall events occurred before the snowpack was established on 14 December. There were no spring rainfall events after the snowpack melted out on 25 May. The total erosivity over the first wet season was 556 MJ mm ha^{-1} h^{-1} as compared to the long-term mean of approximately 340 MJ mm ha^{-1} h^{-1} (Renard et al., 1997). Eighty-two percent of the erosivity in the first wet season was due to a 285 mm storm in early November 2002, which is approximately 6% larger than the estimated 10-year storm of 425 MJ mm ha^{-1} h^{-1} (Renard et al., 1997). The maximum 30-minute rainfall intensity in the first wet season was 11.7 mm h^{-1}.

During the second wet season there were only two small storms prior to the formation of the snowpack on 8 November. The most erosive storm was 8 MJ mm ha^{-1} h^{-1} due to 19 mm of rainfall on 2 November 2003. There was almost no precipitation after 1 March and the snowpack melted out by the end of April. The seven post-melt storms had a total erosivity of only 8 MJ mm ha^{-1} h^{-1}. The annual erosivity was only 21 MJ mm ha^{-1} h^{-1}, or about 4% of the value from the first wet season. The maximum 30-minute rainfall intensity in the second wet season was only 4.3 mm h^{-1}.

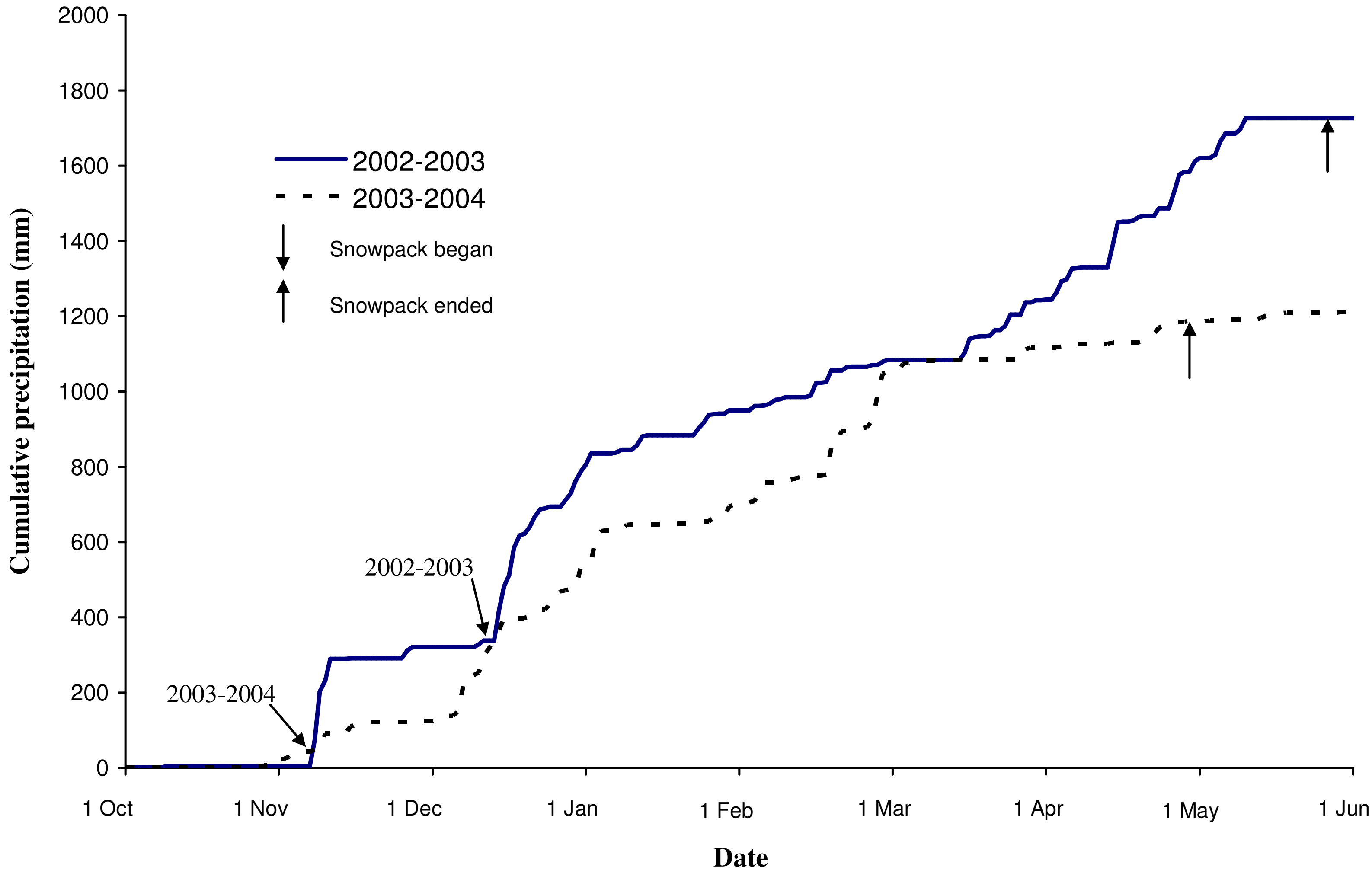

Figure 6. Cumulative precipitation at Hell Hole and the duration of the snowpack at Greek Store for each wet season.

5.2. Contributing area, slope and aspect

The mean contributing area of all burned sites was 0.30 ha, while the range was from 0.01 ha to 1.72 ha. Only three sites were larger than 0.59 ha (Table 3). The mean contributing area was 0.17 ha (s.d.=0.20 ha) for cable-logged sites, 0.31 ha (s.d.=0.25 ha) for helicopter-logged sites, and 0.38 ha (s.d.=0.42 ha) for tractor-logged sites. The differences in mean contributing area between logging treatments were not significant. The lower mean contributing area for cable-logged sites may be partly due to their tendency to be closer to the ridgetops where the cable equipment and landing had to be located. The five unburned control sites were significantly larger, as the mean contributing area was 0.58 ha (s.d.=0.35 ha).

The mean percent slope for the burned sites was 33%, and the range was from 13% to 58% (Table 3). The mean slope was 45% (s.d.=11%) for cable-logged sites, 40% (s.d.=7%) for helicopter-logged sites, and 25% (s.d.=7%) for tractor-logged sites (Table 3). The mean slopes for the cable- and helicopter-logged sites were significantly steeper than the tractor-logged sites ($p<0.001$ for each comparison), but there was not a significant difference in the mean slope between the cable- and helicopter-logged sites. The five unburned control sites had a mean slope of 39% (s.d.=5%), and this was significantly steeper than the tractor-logged sites ($p<0.001$), but not significantly different from the cable- and helicopter-logged sites.

The general southwest to northeast alignment of the ridges largely controlled site aspect. Eighty-four percent of the sites had a north, northwest, south, or southwest aspect (Table 3; Figures 2 and 7).

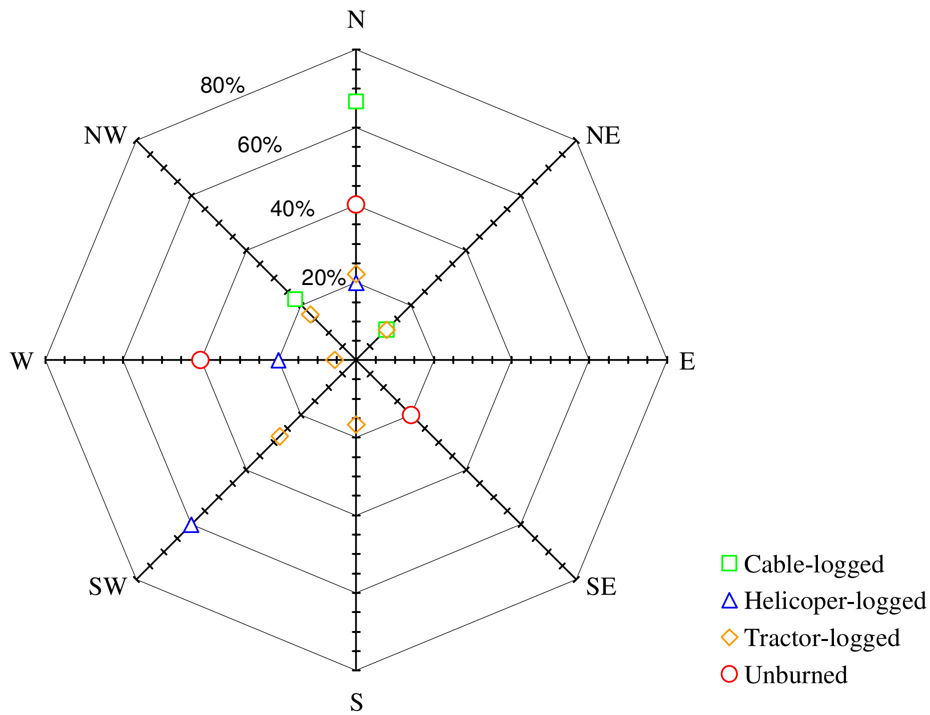

Figure 7. Percent of sites by aspect for each treatment.

5.3. Soil particle-size distribution

The surface soils in the sites were generally coarse. On average, particles larger than 2 mm accounted for 31% of the total mass, while the mean percent sand was 63%. Silt- and clay-sized particles accounted for only 6% of the total mass (Figure 8; Appendix 1a). The overall range of percent coarse material was 20% to 47%, while the range of percent sand was from 48% to 83%, and the percent silt plus clay ranged from 3% to 15% (Appendix 1a). There were no significant differences between logging treatments in the percentages of coarse material, sand, or silt plus clay.

The mean median diameter (D_{50}) for the burned sites was 0.96 mm, while the range for individual sites was from 0.29 mm to 5.8 mm (Appendix 1b). There were no significant differences between logging treatments in the mean D_{16}, D_{50}, or D_{84} values.

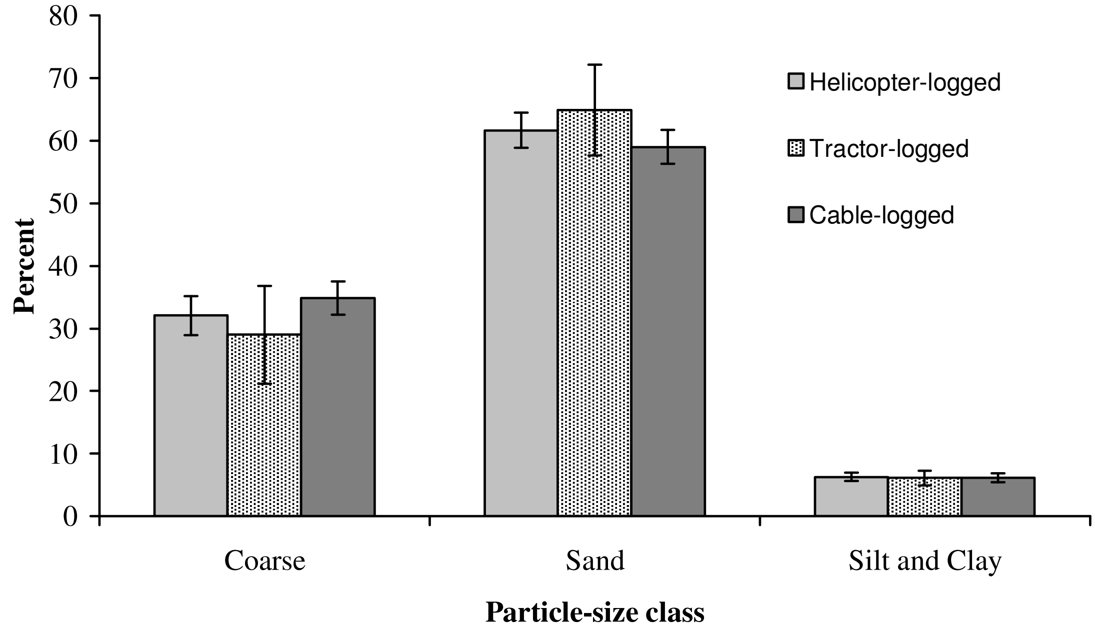

Figure 8. Mean particle-size distribution of the surface soil samples by logging treatment. Bars represent one standard error.

5.4. Ground cover

In summer 2002 the mean percent bare soil for the burned sites was 37%, and the range was from 9% to 55% (Figure 9; Appendix 2a). The unburned sites averaged only 4% bare soil with a maximum value of 12%. The cable-logged sites had slightly more bare soil (46%) than the tractor-logged sites (38%), but this difference was not significant. The 46% bare soil in the cable-logged sites was significantly higher than the percent bare soil in the unlogged cable- and helicopter-suitable sites (29%) and the unlogged tractor-suitable sites (35%) ($p=0.007$ and $p<0.001$, respectively). There were no significant differences in the amount of bare soil between the tractor-logged sites and either set of unlogged sites.

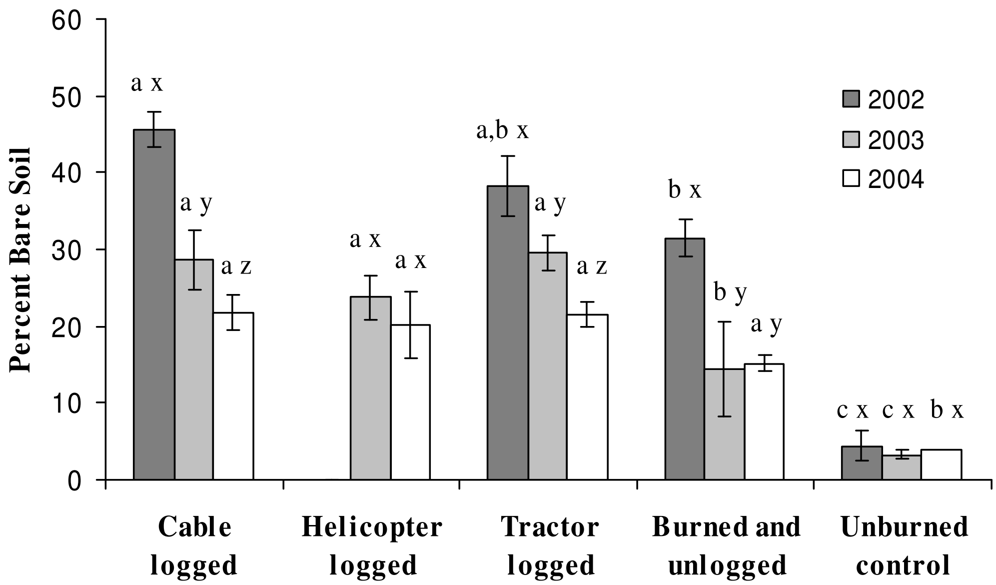

Figure 9. Percent bare soil by treatment for 2002, 2003, and 2004. Bars represent one standard error. Comparisons between treatments within each year are designated by the letters a, b, and c, while comparisons between years within a treatment are designated by the letters x, y, and z. Values with the same letter are not significantly different at $p \leq 0.05$. There were no helicopter-logged sites in summer 2002.

On average, 30% of the area in the burned and unlogged sites was covered with litter <1 cm thick. The corresponding value for the logged sites was 13%, and this difference was significant at $p<0.001$. The logged sites did have significantly more small and large woody debris than the burned and unlogged sites ($p<0.001$). Both the logged and the burned and unlogged sites had approximately 10% live vegetation in summer 2002 (Appendix 2a).

The mean percent bare soil for the burned sites significantly decreased from 37% in 2002 to 27% in 2003 ($p=0.002$) (Figure 9) (Appendix 2a, b). Both the cable- and tractor-logged sites had significantly less bare soil than in 2002. There were no significant differences in mean percent bare soil between cable-, helicopter-, and tractor-logged sites in 2003 (Figure 9). The three burned and unlogged sites averaged 15% bare soil, and this was significantly less than the cable-, helicopter-, and tractor-logged sites (Figure 9).

For the burned sites, the mean amount of live vegetation increased from 10% in 2002 to 25% in 2003 ($p<0.001$). This increase was similar for both the cable- and tractor-logged sites. This increase in percent live vegetation accounts for the observed reduction in percent bare soil, as there were no other significant changes in any of the ground cover classes between summer 2002 and 2003 (Appendix 2a, b).

From 2003 to 2004, the mean percent bare soil for the burned sites declined from 27% to 21% ($p=0.009$). Both the cable- and tractor-logged sites had significantly less bare soil than in 2003 (Figure 9). There were no significant differences in the mean percent bare soil between cable-logged, helicopter-logged, or tractor-logged sites in 2004 (Figure 9). The mean amount of live vegetation increased from 25% in 2003 to 36% in 2004 and this increase was significant ($p<0.001$) (Appendix 2b, c). Tree planting had no significant effect on the percentage of live vegetation. When stratified by treatment, there was a significant increase in the amount of vegetation for the cable- and tractor-logged sites ($p<0.001$ for each comparison), but not in the helicopter-logged sites.

5.5. Ground disturbance

The mean amount of ground disturbance was 29% for the tractor-logged sites, 24% for the cable-logged sites, and 4% for the helicopter-logged sites (Figure 10; Appendix 3). The helicopter-logged sites had significantly less disturbance than the tractor- and cable-logged sites ($p=0.001$), but there was no significant difference in the amount of ground disturbance between the tractor- and cable-logged sites ($p=0.45$).

When the tractor-logged sites were stratified by landowner, the mean percent disturbance was 22% for sites on public lands and 31% for the sites on private lands, but this difference was not significant (p=0.20). Similarly, the mean percent disturbance for the cable-logged sites on public lands was 13% versus 27% for cable-logged sites on private lands. Since there were only two cable-logged sites on public lands, this two-fold difference in ground disturbance was not significant (p=0.08). In 2003, percent bare soil was weakly but significantly related to percent disturbance (R^2=0.13; p=0.05).

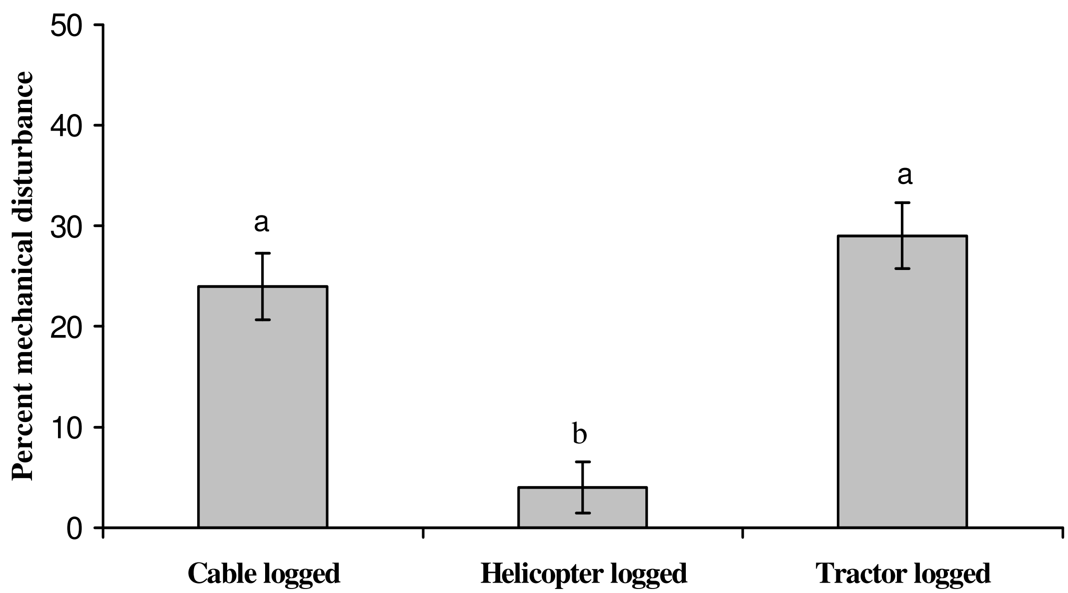

Figure 10. Percent disturbed ground for the summer after logging by treatment. Bars represent one standard error. Values with the same letter are not significantly different at $p \leq 0.05$.

5.6. Soil water repellency

Larger CST values indicate less soil water repellency, and a value of 72.8 dynes cm^{-1} indicates no water repellency. The mean soil water repellency on unburned sites was strongest at the mineral surface and progressively weaker with increasing depth

(Figure 11a). This is most likely due to the leaching of hydrophobic compounds from the surface organic matter. The burned sites also exhibited progressively weaker soil water repellency with increasing depth in 2002, 2003, and 2004 (Figure 11b,c,d). The CST values varied greatly between pits and between burned sites (Figure 11; Appendix 4).

In summer 2002, the mean CST values were significantly lower in the burned sites than the unburned sites at 0, 2.5 and 5 cm (Appendix 4a). There were no significant differences at 7.5, 10 and 12.5 cm.

Between 2002 and 2003, the soil water repellency in the burned sites significantly decreased at 2.5, 5, and 7.5 cm (Table 4). This increase in CST values meant that there were no significant differences in soil water repellency at any depth between the burned and unburned sites in 2003.

Between 2003 and 2004, there were no significant changes in the mean CST values for the burned sites (Table 4). In summer 2004, the mean CST values were significantly lower in the burned sites than in the unburned sites at 10 and 12.5 cm. This difference is due to the higher CST values in the unburned sites in summer 2004 than in previous years. The higher CST values at 10 and 12.5 cm in the unburned sites may be due to a decrease in hydrophobic fungal mycelia caused by the lower amount of precipitation in the second wet season.

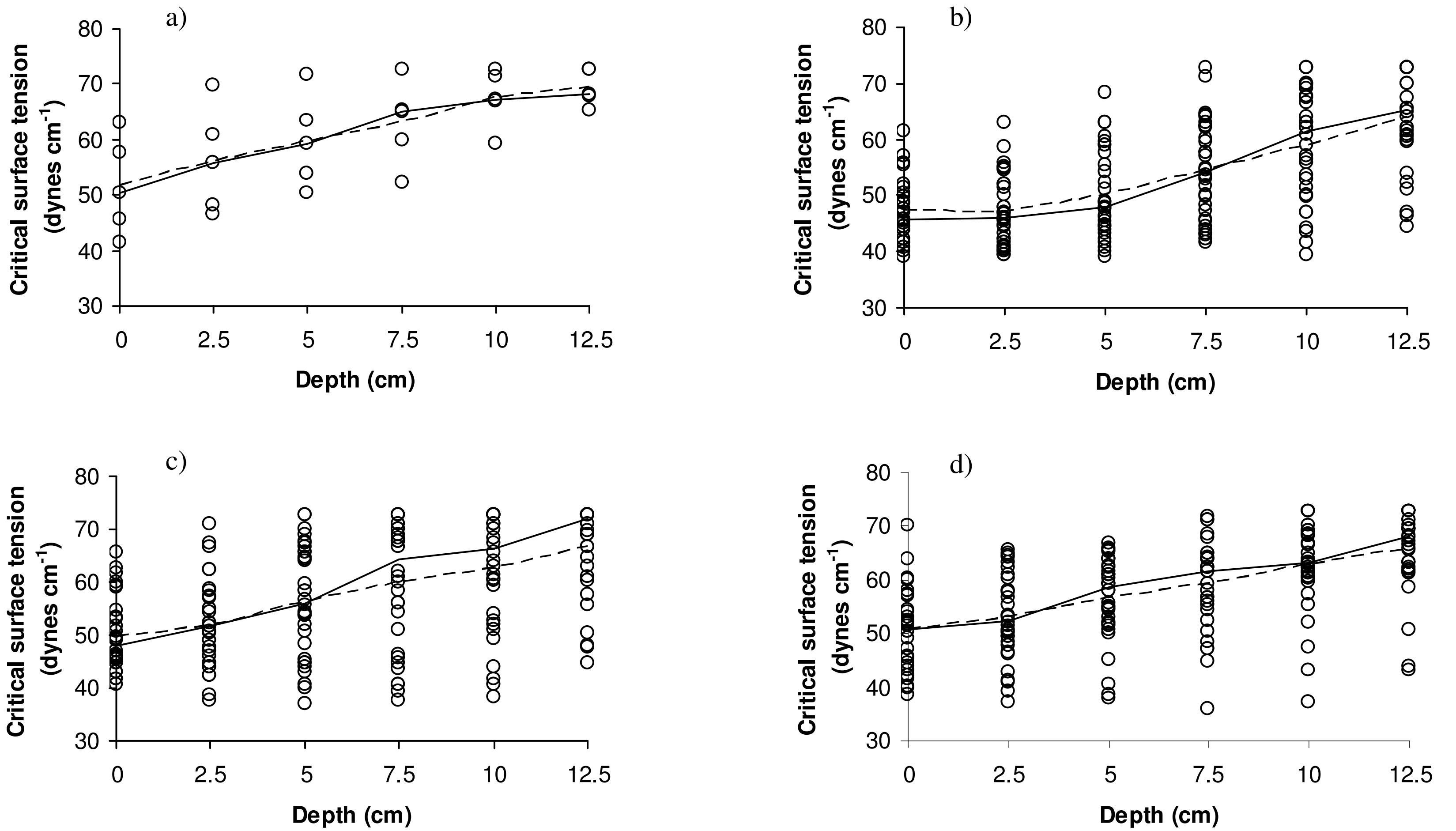

Figure 11. Critical surface tension (CST) values by depth for: a) unburned sites (mean of 2002-2004; n=5); b) burned sites in 2002 (n=32); c) burned sites in 2003 (n=32); and d) burned sites in 2004 (n=32). Each circle represents the average value at a site. The mean values are plotted as dashed lines and median values are plotted as solid lines. A decrease in CST indicates stronger water repellency.

Depth (cm)	CST: summer 2002 (dynes cm^{-1})	CST: summer 2003 (dynes cm^{-1})	CST: summer 2004 (dynes cm^{-1})
0	47.2 (5.5) a	49.7 (6.7) a	50.6 (7.7) a
2.5	47.1 (6.2) a	51.8 (8.3) b	52.9 (8.0) b
5	50.1 (7.7) a	56.4 (10.4) b	56.5 (7.9) b
7.5	54.5 (8.7) a	59.9 (11.9) b	59.2 (8.4) b
10	58.9 (9.9) a	62.7 (11.2) a	62.8 (8.4) a
12.5	64.1 (8.8) a	66.6 (8.8) a	65.7 (7.7) a

Table 4. Mean critical surface tension (CST) values for all burned study sites by depth for each year. Comparisons are between years for each depth. Values with the same letter at each depth are not significantly different at $p \leq 0.05$. Standard deviations are shown in parentheses.

The measurements of soil water repellency on the skid trails and cable rows in summer 2003 indicated only very weak soil water repellency at 0 and 2.5 cm (Appendix 4d, e). At each depth, the mean CST values for skid trails and cable rows were significantly greater than the mean values for both burned and unburned sites ($p<0.01$). These differences indicate that high levels of soil disturbance can break up soil water repellency.

5.7. Soil compaction

The mean unconfined soil strength for the 10 skid trails was 1.16 kg cm^{-2}, and the mean for each skid trail ranged from 0.63 kg cm^{-2} to 1.8 kg cm^{-2} (s.d.=0.37 kg cm^{-2}) (Table 5a; Appendix 5). The mean unconfined compressive soil strength for the adjacent undisturbed sites was only 0.37 kg cm^{-2} (s.d.=0.10 kg cm^{-2}), and this difference was highly significant ($p=0.001$). Each skid trail also had a significantly higher mean unconfined compressive soil strength than the adjacent undisturbed areas.

The mean unconfined compressive soil strength for the 6 cable rows was 0.16 kg cm^{-2}, and the mean for each cable row ranged from 0.12 kg cm^{-2} to 0.20 kg cm^{-2} (s.d.=0.03 kg cm^{-2}) (Table 5b; Appendix 5). The overall mean unconfined compressive soil strength on the adjacent undisturbed sites was about 30% lower, and this difference was significant ($p=0.039$). However, 2 of the 6 cable rows did not have a significantly greater ($p \leq 0.05$) unconfined compressive soil strength than the adjacent undisturbed areas, indicating that partially suspended cable logging does not always cause soil compaction.

The mean unconfined compressive soil strength from the undisturbed areas adjacent to the skid trails in summer 2003 was more than three times the value for the undisturbed areas adjacent to the cable rows as measured in 2004. The cause of this difference is not known as the same measurement procedure was used in each year, and there was no evidence of disturbance on the sites classified as being undisturbed.

a)

Site	Logging treatment	Mean compressive strength on skid trails (kg cm^{-2})	Mean compressive strength on adjacent undisturbed sites (kg cm^{-2})
MF-9-South	Tractor	0.63	0.36
CR-Creek-1	Tractor	0.93	0.51
FM-3	Tractor	1.80	0.33
CR-Creek-2	Tractor	1.47	0.36
CR-West-3	Tractor	1.40	0.48
MF-7-South	Tractor	0.73	0.29
CR-1-NE	Tractor	1.19	0.54
LC-5-North	Tractor	0.81	0.27
LC-6-North	Tractor	1.31	0.35
MF-3	Tractor	1.36	0.24
Mean		**1.16**	**0.37**
Standard deviation		**0.37**	**0.10**

b)

Site	Logging treatment	Mean compressive strength on cable rows (kg cm^{-2})	Mean compressive strength on adjacent undisturbed sites (kg cm^{-2})
MF-1, 1	Cable	0.20	0.11
MF-1, 2	Cable	0.12	0.08
MF-2, 1	Cable	0.15	0.09
MF-2, 2	Cable	0.16	0.09
MF-2-South, 1	Cable	0.15	0.15
MF-2-South, 2	Cable	0.18	0.17
Mean		**0.16**	**0.11**
Standard deviation		**0.03**	**0.04**

Table 5. Mean unconfined compressive soil strength on cable rows, skid trails, and adjacent undisturbed areas for: a) tractor-logged sites; and b) cable-logged sites.

5.8. Sediment production

Sediment production was positively and significantly correlated to contributing area for both the first wet season (R^2=0.78; p<0.001) and the second wet season (R^2=0.62; p<0.001) (Figure 12). Given the strength of these relationships, the sediment production data were normalized by contributing area.

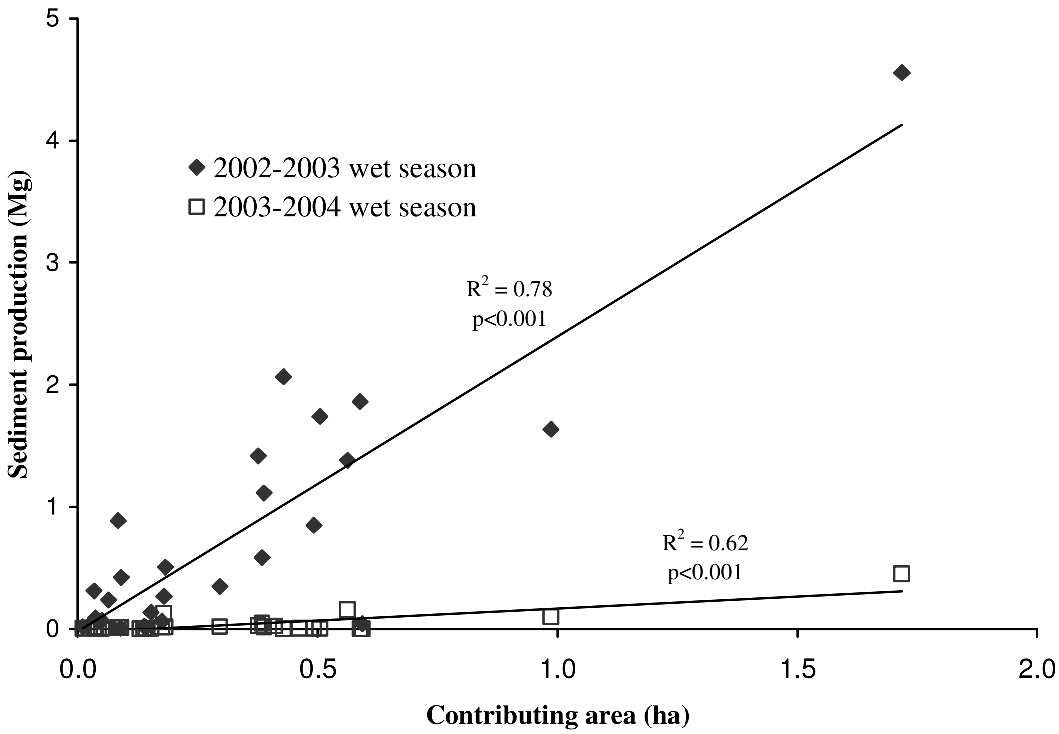

Figure 12. Sediment production versus contributing area for the 2002-2003 and 2003-2004 wet seasons.

The mean sediment production rate in the first wet season for the unburned study sites was 0.006 Mg ha^{-1}, as LC-2-South was the only site to produce any sediment (Table 6; Figure 13a). The mean sediment production rate for the burned sites was 2.6 Mg ha^{-1}, and the range was from 0.07 Mg ha^{-1} to 10.6 Mg ha^{-1} (Table 6; Appendix 6a). When stratified by treatment, the mean sediment production rate from cable-logged sites

Site ID	Treatment	2002-2003 sediment (kg)	2002-2003 sediment production (Mg ha^{-1})	2002-2003 sediment (kg)	2002-2003 sediment production (Mg ha^{-1})
HH-1	Unburned	0	0.00	0	0.00
LC-1-South	Unburned	0	0.00	0	0.00
LC-2-South	Unburned	21	0.03	0	0.00
RR-1-North	Unburned	0	0.00	0	0.00
RR-2-North	Unburned	0	0.00	0	0.00
Mean		**4**	**0.006**	**0**	**0.00**
Median		**0**	**0.000**	**0**	**0.00**
Standard deviation		**10**	**0.013**	**0**	**0.00**
CR-17N12YL-1	Cable-logged	1858	3.16	1	0.00
MF-1	Cable-logged	21	0.15	0	0.00
MF-1-South	Cable-logged	87	2.34	3	0.08
MF-2	Cable-logged	6	0.07	9	0.10
MF-2-South	Cable-logged	310	9.14	13	0.37
MF-3	Cable-logged	2064**	4.81	0	0.00
MF-3-South	Cable-logged	68	1.35	4	0.09
MF-4	Cable-logged	884	10.6	12	0.14
MF-4-South	Cable-logged	423	4.67	9	0.10
Mean		**636**	**4.00**	**6**	**0.10**
Median		**310**	**3.20**	**4**	**0.09**
Standard deviation		**802**	**3.70**	**5**	**0.11**
CR-West-2	Helicopter-logged	183*	0.44	21	0.05
FM-1	Helicopter-logged	NA	NA	7	0.12
LC-1-North	Helicopter-logged	583	1.52	47	0.12
LC-2-North	Helicopter-logged	1378	2.45	154	0.27
LC-3-North	Helicopter-logged	849	1.72	4	0.01
Mean		**748**	**1.90**	**47**	**0.12**
Median		**849**	**1.70**	**21**	**0.12**
Standard deviation		**405**	**0.50**	**63**	**0.10**
CR-1-NE	Tractor-logged	62	0.35	12	0.07
CR-1-North	Tractor-logged	1113	2.87	15	0.04
CR-2-North	Tractor-logged	348	1.17	16	0.05
CR-5-North	Tractor-logged	18	1.67	5	0.46
CR-7-North	Tractor-logged	59	1.37	4	0.09
CR-Creek-1	Tractor-logged	1633	1.66	99	0.10
CR-Creek-2	Tractor-logged	4555	2.65	452	0.26
CR-Creek-3	Tractor-logged	135	0.89	3	0.02
CR-West-3	Tractor-logged	1740**	3.45	1	0.00
FM-3	Tractor-logged	266	1.48	124	0.69
FM-4	Tractor-logged	NA	NA	0	0.00
LC-5-North	Tractor-logged	1417	3.77	24	0.06
LC-6-North	Tractor-logged	373***	0.81	6	0.01
MF-6-South	Tractor-logged	238	3.74	7	0.11
MF-7-South	Tractor-logged	42	0.07	0	0.00
MF-8-South	Tractor-logged	12	0.08	1	0.01
MF-9-South	Tractor-logged	504	2.75	15	0.08
Mean		**809**	**1.90**	**46**	**0.12**
Median		**266**	**1.70**	**7**	**0.06**
Standard deviation		**1170**	**1.30**	**110**	**0.19**
CR-West-1	Burned unlogged	80	0.70	2	0.02
FM-1	Burned unlogged	24	0.40		
FM-4	Burned unlogged	10	0.10		
Mean		**38**	**0.40**		
Median		**38**	**0.40**		
Standard deviation		**37**	**0.30**		

Table 6. Sediment production by site and treatment for the 2002-2003 and 2003-2004 wet seasons. Mean, median and standard deviation calculations exclude fences that failed or were destroyed by logging. NA indicates not applicable for that year. * indicates fence destroyed by logging, ** indicates fence overtopped, and *** indicates fence failed.

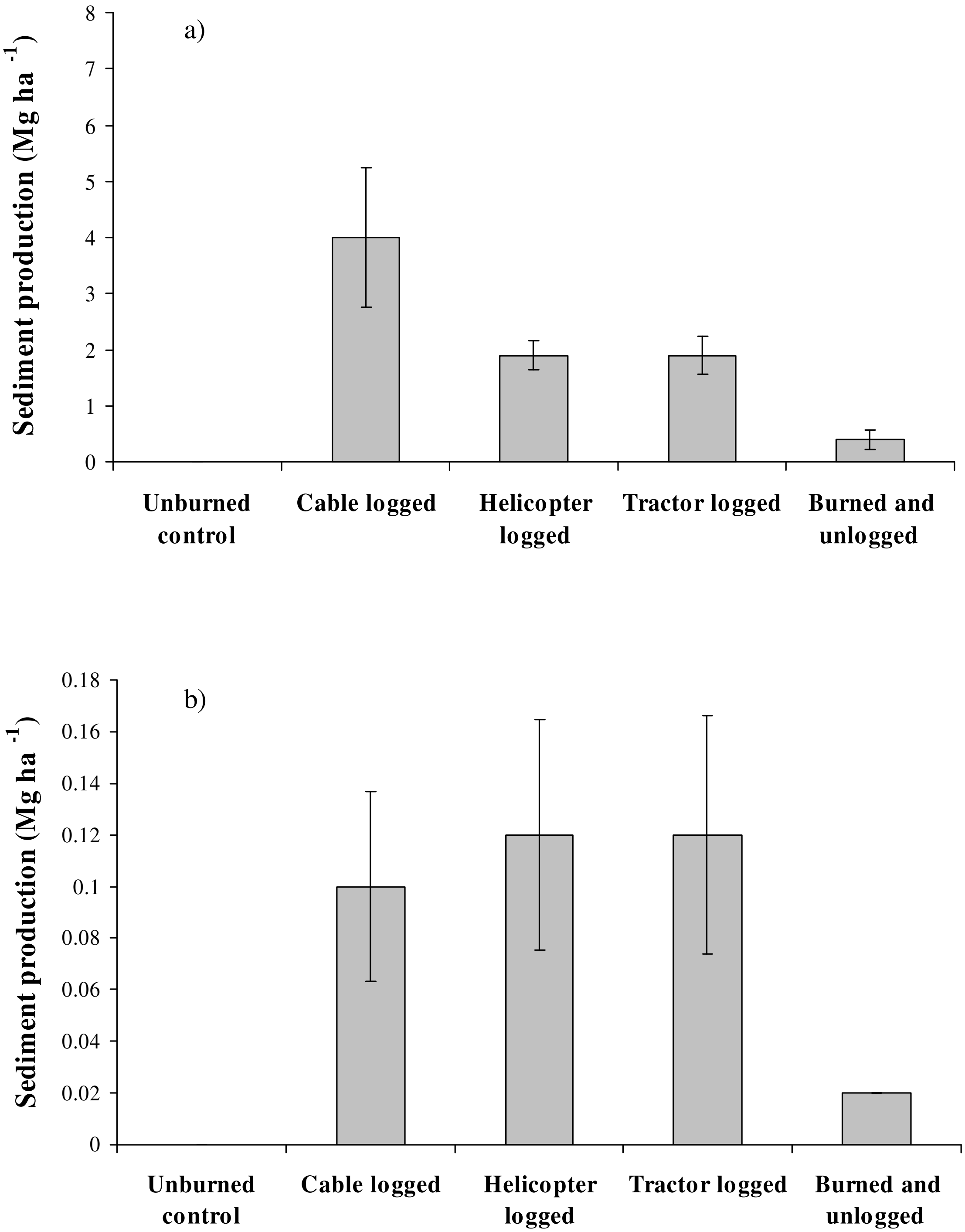

Figure 13. Sediment production rates by treatment for: a) 2002-2003 wet season, and b) 2003-2004 wet season. Bars represent one standard error.

was 4.0 Mg ha^{-1}, or slightly more than twice the value of 1.9 Mg ha^{-1} that was measured for both the helicopter-logged sites and the tractor-logged sites (Figure 13a). The relatively high value for the cable-logged sites was due to two sites that each generated approximately 10 Mg ha^{-1} of sediment. These high rates were presumably due to the sites having approximately 30% ground disturbance and 50% bare soil. If these two sites are excluded, the mean sediment production rate for cable-logged sites drops to 2.4 Mg ha^{-1}. The differences in sediment production rates between logging treatments were not significant due to the large variability between sites. The skew in the data means that the median sediment production rates were about 10-20% lower than mean values.

The mean sediment production rates from the three logging treatments were approximately 5 to 10 times higher than the mean sediment production rate of 0.4 Mg ha^{-1} for the three burned and unlogged sites. The lower sediment production rate from the burned and unlogged sites may be due to the fact that these sites averaged only 28% bare soil versus 38% for the burned and logged sites. The smaller amount of bare soil on the burned and unlogged sites is mainly due to a higher percentage of litter <1 cm thick.

The large storm in November 2002 accounted for 82% of the total rainfall erosivity in the 2002-2003 wet season. The mass of sediment was measured at five sites immediately after this storm, and these values accounted for 77% to 97% of the total sediment from these sites in the first wet season (Appendix 6c).

In the second wet season, none of the unburned study sites produced any sediment (Table 6; Figure 13b). The mean sediment production rate from the burned study sites was 0.11 Mg ha^{-1} or just 4% of the value from the first wet season, and the range was from 0 Mg ha^{-1} to 0.69 Mg ha^{-1} (Table 6; Appendix 6b). The mean sediment production rates from the three logging treatments were similar, and the low values meant that there was relatively more site-to-site variability than in the first wet season (Figure 13b).

For each logging treatment, the mean sediment production rate in the second wet season was significantly less than in the first wet season (Figure 13). The mean sediment production rate for each logging treatment also was at least 5 times higher than the sediment production rate of 0.02 Mg ha^{-1} measured from the one burned and unlogged study site. Again, the lower sediment production rate from the unlogged site is presumably due to the smaller amount of bare soil (17%) compared to the burned and logged sites (27%).

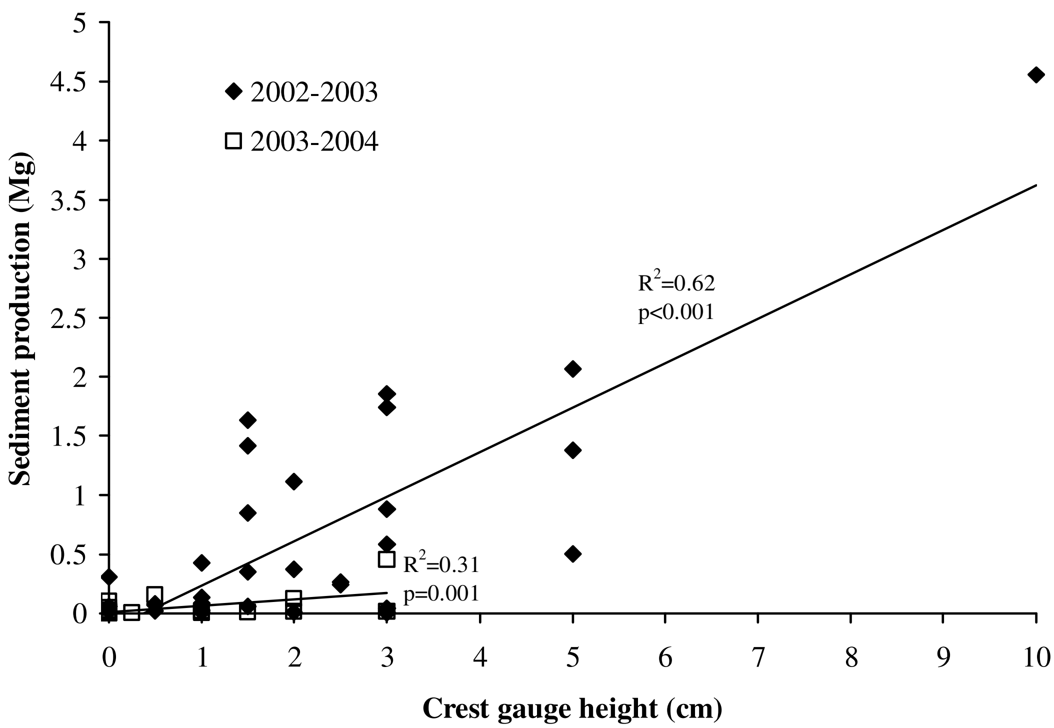

Figure 14. Sediment production versus crest gauge height for the 2002-2003 and 2003-2004 wet seasons.

In the first wet season, the mean sediment production rate from the cable-logged sites on private lands was 5.2 Mg ha^{-1} versus 0.11 Mg ha^{-1} from the sites on public lands ($p=0.008$). This was mainly due to the fact that the two cable-logged sites that generated approximately 10 Mg ha^{-1} of sediment were each on private land. If these two sites are excluded, there is no significant difference in the mean sediment production rates by land owner. For the tractor-logged sites, the mean sediment production rate in the first wet season was 1.7 Mg ha^{-1} for sites on private lands and 2.7 Mg ha^{-1} for sites on public lands, but this difference was not significant ($p=0.33$).

In the second wet season, mean sediment production rates from cable-logged sites on private lands were twice the value from public lands, but this difference was not significant. For tractor-logged sites, the mean sediment production rates from public and private lands were nearly identical. All of the helicopter-logged sites were on public lands, so a comparison of sediment production rates by landowner was not possible.

Sediment production was very strongly correlated with crest gauge height in the first wet season ($R^2=0.64$; $p<0.001$) (Figure 14). In the second wet season, the relationship was much weaker ($R^2=0.31$; $p=0.001$). The weaker relationship is probably due to the much smaller range of values as the highest crest gauge reading was only 3 cm and the highest sediment yield was approximately 0.5 Mg.

Sediment production rates were normalized by erosivity and area in order to facilitate comparisons between wet seasons. For the burned and logged sites, the mean sediment production rate was 4.7×10^{-4} kg per MJ mm ha^{-1} h^{-1} m^{-2} in the first wet season, and about 15% higher in the second wet season. The similarity of these values is surprising given that the percent bare soil decreased by 10%. There were no significant differences in the normalized sediment production rates between wet seasons for each logging treatment, or between logging treatments for each wet season.

5.9. Bulk density, rill density, rill erosion, and erosion pins

Bulk densities on the 12 cable- and tractor-logged sites ranged from 910 kg m^{-3} to 1110 kg m^{-3} with a mean of 980 kg m^{-3} (Appendix 7). The overall mean standard deviation was 71 kg m^{-3}, and the range of standard deviations for individual sites was from 50 kg m^{-3} to 150 kg m^{-3}. The mean bulk density for tractor-logged sites was 3% higher than the cable-logged sites, but this difference was not significant.

Field observations indicate that the majority of the rills in the burned areas formed during the 2002-2003 wet season in topographically convergent areas, such as the swale axes. In the unburned swales there was no evidence of new or historic rill formation. The length of rills at each site was positively and significantly correlated with contributing area (R^2=0.25; p=0.003). This relationship was slightly improved by multiplying the contributing area by the slope (R^2=0.30; p=0.001) (Figure 15).

Rill densities in summer 2004 ranged from 0.00 m m^{-2} to 0.060 m m^{-2} with a mean of 0.014 m m^{-2} (Appendix 8). The highest rill density was in cable-logged sites at 0.025 m m^{-2}, and the tractor-logged sites had the lowest mean rill density at 0.0090 m m^{-2}. The mean rill density of the helicopter-logged sites was 0.012 m m^{-2}. The only significant difference was between the cable- and tractor-logged sites (p=0.023). Sediment production rates in each wet season were not significantly related to rill density.

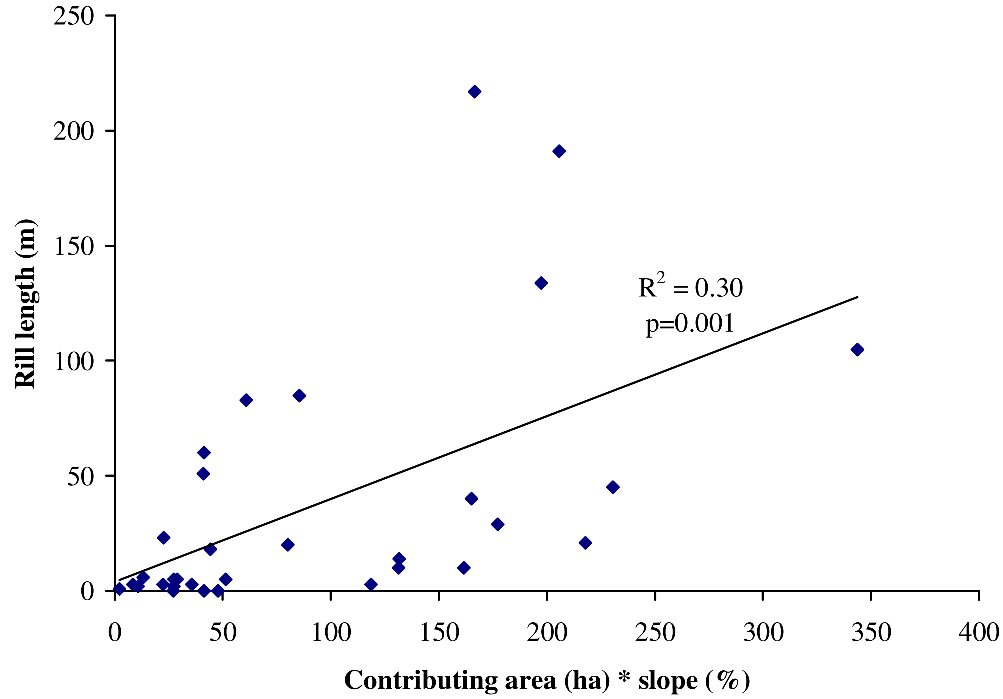

Figure 15. Rill length in summer 2004 versus contributing area times slope.

The calculated rill erosion between summer 2003 and 2004 ranged from 0.001 Mg to 1.05 Mg, with a mean of 0.50 Mg (Table 7). For three sites, the calculated rill erosion greatly overestimated the mass of sediment collected in the fences (Table 7). At the other two sites, the calculated rill erosion accounted for 50% and 10% of the sediment collected in the fence, respectively. The large variability suggests that the number of cross-sections per rill did not adequately characterize rill erosion, and that rill erosion may not be the dominant erosion process in some areas.

Of the 12 sites with erosion pins, six had net deposition and six had net erosion. The net elevation change per plot ranged from +3 mm to -25 mm with a mean of -2.1 mm (positive values indicate deposition) (Table 8). If the erosion pin data are extrapolated to the entire plot, the mean deposition in the six plots with positive values was 11 Mg, and the range was from 0.22 Mg to 50 Mg (Table 8).

Site	Rill length (m)	Total mass removed by rill incision (Mg)	Mass collected by fence (Mg)	Ratio of eroded mass to collected mass
CR-Creek-1	29	1.0	0.099	11
CR-Creek-2	18	0.22	0.453	0.50
CR-West-3	109	0.90	0.001	900
MF-3	64	0.31	0.001	310
MF-9-South	13	0.001	0.015	0.098

Table 7. Rill length, rill erosion, and the ratio of rill erosion to sediment production for the 2003-2004 wet season.

For the sites with net erosion, the mean erosion was 7 Mg and the range was from 0.45 Mg to 14 Mg (Table 8). These erosion values are much greater than the mass collected from the fences. This means that only a small portion of the interrill erosion is reaching the fences, or that the measured interrill erosion rates may not be representative of the entire plot. The latter explanation is supported by the fact that 6 plots had net deposition but still generated from 0.004 to 0.45 Mg of sediment.

Site	Mean elevation change (mm)	Calculated interill erosion (Mg)	Mass collected in fence (Mg)	Ratio of eroded mass to collected mass
CR-1-NE	-0.27	-0.45	0.012	-36
CR-5-North	-0.62	-1.8	0.005	-370
CR-7-North	+0.64	+0.31	0.004	+80
CR-Creek-1	+1.0	+9.9	0.099	+100
CR-Creek-2	+3.0	+50	0.453	+110
CR-Creek-3	+2.0	+3.1	0.003	+900
CR-West-3	-2.65	-14	0.001	-14000
MF-1-South	+0.77	+0.22	0.003	+76
MF-3	-2.82	-11	0.001	-22000
MF-3-South	-25.3	-13	0.004	-3000
MF-6-South	-1.28	-0.98	0.007	-130
MF-9-South	+0.60	+1.0	0.015	+67

Table 8. Mean elevation change, calculated interill erosion, and the ratio of interrill erosion to sediment production for the 2003-2004 wet season. Positive values indicate deposition.

5.10. Modeling sediment production

Percent bare soil was strongly correlated with the logarithm of sediment production per unit area for the burned and logged study sites for the first wet season (R^2=0.41; p=0.002) (Figure 16), but not for the second wet season (R^2=0.001). When stratified by treatment and year, there was a significant relationship between percent bare soil and sediment production only for the cable-logged sites in the first wet season (R^2=0.80; p=0.001).

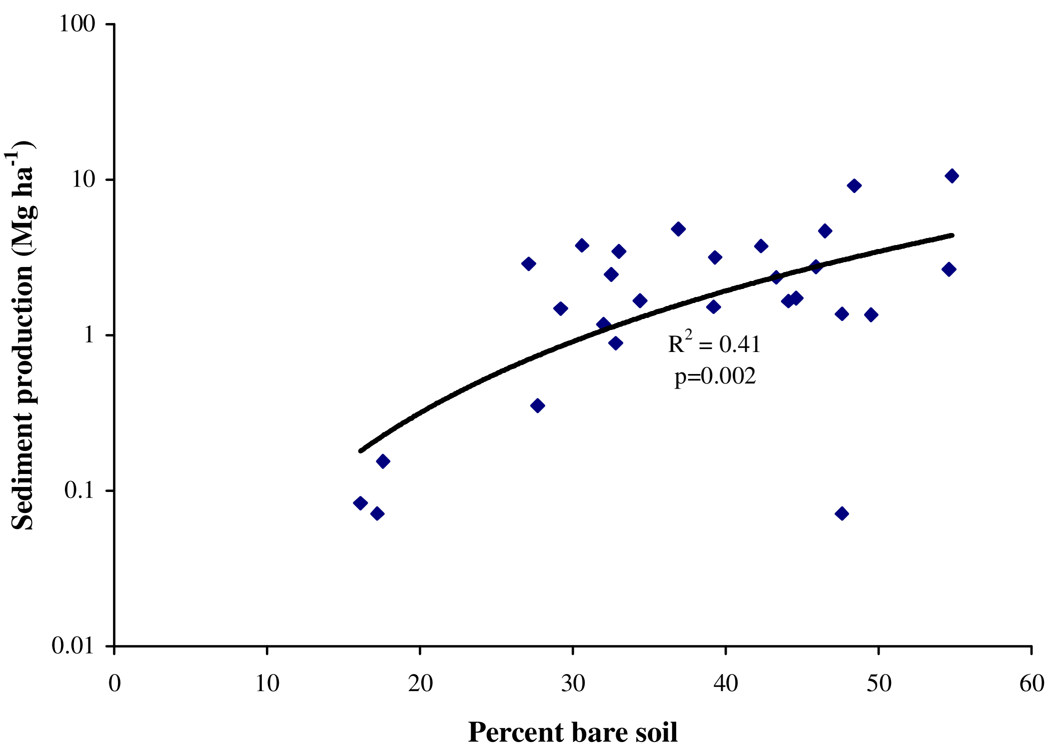

Figure 16. Sediment production versus percent bare soil for the 2002-2003 wet season.

There was no significant correlation between percent disturbance and sediment production from the burned and logged sites for the first or second wet seasons. If the data are stratified by treatment and year, only the cable-logged sites in the first wet season had a significant relationship between disturbance and sediment production (R^2 =0.47; p=0.042). Slope was not significantly correlated with sediment production when stratified by treatment and year or when separated into slope classes within treatments. There were no significant correlations between any of the independent variables and sediment production normalized by erosivity and area.

The best empirical model for estimating the annual sediment production included six variables: logarithm of contributing area, percent bare soil, percent litter <1 cm thick, annual erosivity, CST value at 0 cm, and soil D_{50} (Table 9). The overall model R^2 was 0.76 and the root mean square error (RMSE) of the model was 0.52 (Table 10). This model has a slight tendency to over-predict lower values of sediment production and under-predict higher values (Table 10; Figure 17). The model indicates that sediment production increases with increasing contributing area, percent bare soil, annual rainfall erosivity, and soil D_{50}, and decreases with increasing litter <1 cm thick and CST at 0 cm (weaker soil water repellency).

Two progressively simpler empirical models were developed to predict sediment production by removing variables with low partial R^2. The best 4-parameter model had a R^2 of 0.72 as compared to 0.76 for the complete model, and this used the logarithm of area, percent bare soil, annual erosivity, and the CST value at 0 cm (Table 9). The RMSE was only slightly higher at 0.55 (Table 10; Figure 17). The best 3-parameter model dropped the CST value but retained the logarithm of the contributing area, percent bare soil, and annual rainfall erosivity (Table 9). The model R^2 decreased to 0.64 and the RMSE increased to 0.62 (Table 10; Figure 17). The best 2-parameter model used the logarithm of contributing area and annual rainfall erosivity. The R^2 was 0.60 and the RMSE was 0.64.

Model	Regression equation	Model R^2
Complete model	Log_{10} sediment production (Mg) = 0.374 + [0.547 * Larea (ha)] + [0.0180 * Bare] - [0.03030 * Litter] + [0.00208 * Eros (MJ mm ha^{-1} h^{-1})] - [0.0477 * CST_0 (dynes cm^{-1})] + [0.219 * D_{50} (mm)]	0.76
4-parameter	Log_{10} sediment production (Mg) = 0.301 + [0.604 * Larea (ha)] + [0.0229 * Bare] + [0.00186 * Eros (MJ mm ha^{-1} h^{-1})] - [0.0512 * CST_0 (dynes cm^{-1})]	0.72
3-parameter	Log_{10} sediment production (Mg) = -2.050 + [0.673 * Larea (ha)] + [0.0181 * Bare] + [0.00222 * Eros (MJ mm ha^{-1} h^{-1})]	0.64

Table 9. Regression equations developed to predict sediment production in Mg from sites burned at high severity and subjected to salvage logging (n=56). Larea is the logarithm of contributing area, Bare is percent bare soil, Litter is the percent of area with litter <1 cm thick, Eros is the annual rainfall erosivity, CST_0 is the critical surface tension at 0 cm, and D_{50} is the median particle size.

Complete model			4-parameter model			3-parameter model		
Variable	p-value	R^2	Variable	p-value	R^2	Variable	p-value	R^2
Log area	0.0005	0.11	Log area	0.0002	0.11	Log area	0.0002	0.11
Percent bare soil	0.0222	0.23	Percent bare soil	0.0025	0.23	Percent bare soil	0.0286	0.23
Litter <1 cm	0.0204	<0.01	Erosivity	<0.0001	0.29	Erosivity	<0.0001	0.29
Erosivity	<0.0001	0.31	CST at 0 cm	0.0003	0.09			
CST at 0 cm	0.0004	0.09						
D_{50}	0.0359	0.02						
Overall model	<0.001	0.76	Overall model	<0.001	0.72	Overall model	<0.001	0.64
Root mean square error		0.52	Root mean square error		0.54	Root mean square error		0.62

Table 10. Statistics for the empirical models developed to predict sediment production from areas burned at high severity.

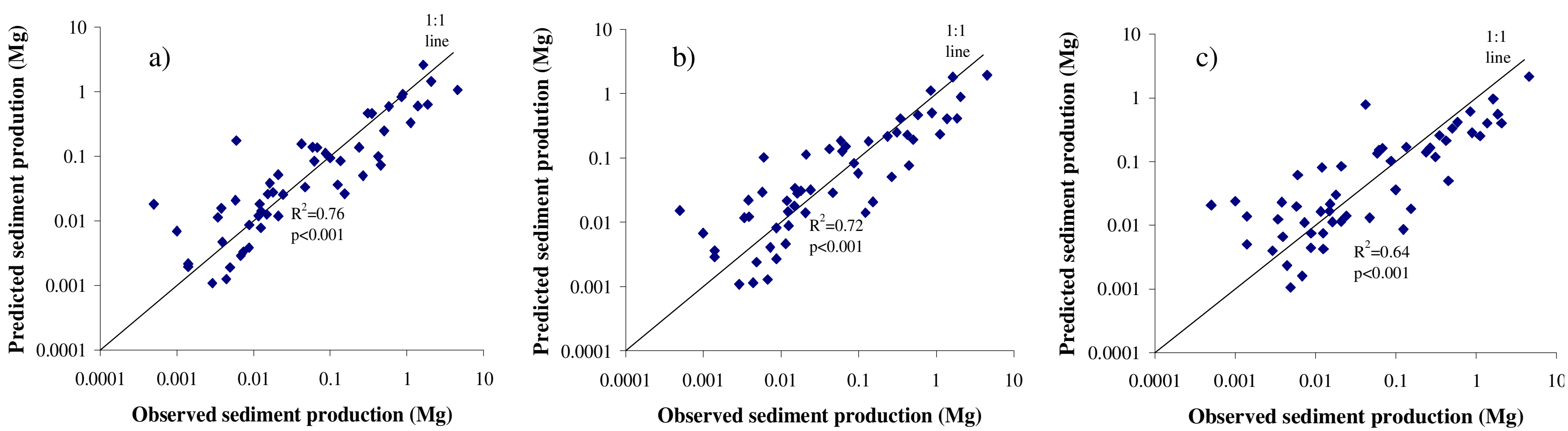

Figure 17. Predicted versus observed sediment production for: a) complete model; b) 4-parameter model; and c) 3-parameter model.

6. DISCUSSION

6.1. Effects of salvage logging

From a management perspective, it is critical to determine the extent to which salvage logging increases or decreases erosion rates. This study identifies several effects of post-fire salvage logging that may increase erosion rates, including an increase in the amount of bare soil, an increase in the amount of ground disturbance, an increase in rill erosion, and compaction on skid trails and cable rows.

In summer 2002 the logged sites had 41% bare soil compared to 31% for the unlogged sites. Most of this difference is due to less litter <1 cm thick on the logged sites compared to the unlogged sites (14% versus 30%). Rainfall simulations indicate that needlecast <1 cm thick on 30% of the surface reduces interrill erosion by almost 40% (Pannkuk and Robichaud, 2003). The differences in bare soil are important as this and other studies have shown that percent bare soil is a very important control on post-fire sediment production rates (Libohova, 2004; Benavides-Solorio and MacDonald, 2005).

In each wet season, the logged sites produced more than 5 times as much sediment as the unlogged site(s). For the first wet season, the complete model predicted that the logged sites would produce twice as much sediment as the unlogged sites. Predicted values were higher for the logged sites because they generally had less litter cover and more bare soil. The observed difference in sediment production between the logged and unlogged sites is about 2.5 times larger than the predicted difference, and this may be due to the disturbance induced by logging. The problem is that there were only three burned and unlogged sites in the first wet season, and only one such site in the second wet season.

Additional analyses indicate the difficulty of making simple generalizations about the effects of salvage logging on site conditions and sediment production rates. For example, the helicopter-logged sites had significantly less bare soil than the tractor-logged sites in the first wet season, but the mean sediment production rates were identical. The relatively high sediment production rates on the helicopter-logged sites may be due to differences in the amount and types of disturbance. On the tractor-logged sites, disturbance perpendicular to the slope often acted as sediment traps, while on helicopter-logged sites there was little disturbance and the relatively smooth slopes resulted in higher rill densities and presumably higher rill and interrill erosion rates.

Percent disturbance was significantly correlated with percent bare soil in summer 2002 and summer 2003, but not in summer 2004. In summer 2002, the correlation between disturbance and bare soil was most likely due to the disruption of litter <1 cm thick during logging. The amount of mechanical disturbance varied by logging treatment, and the mean values of disturbance for tractor- and cable-logged sites in the first year of this study are similar to the values reported from the Entiat fire (Klock, 1975) and the Stanislaus fire (Chou et al., 1994a) (Figure 18). Similarly, the mean percent disturbance for helicopter-logged sites is similar to the value from the Entiat fire (Figure 18). There were no helicopter-logged sites on the Stanislaus fire. The salvage-logged sites on the Star fire produced 25% to 75% more sediment per unit area than the salvage-logged sites on either the Entiat fire or the Stanislaus fire. The similarity in disturbance values between studies, when combined with differences in sediment production rates, suggests that the pattern of disturbance may be important in explaining the differences in sediment production due to salvage logging.

Field observations on the Star fire indicate that skid trails and cable rows oriented perpendicular to a slope tended to act as sediment traps, while the skid trails and cable rows parallel to a slope tended to serve as conduits for concentrated flow that can initiate rills and increase sediment production. A similar study in Australia found that salvage logging after wildfire promoted concentrated flow pathways in areas without topographic convergence, and these flow paths led to rill initiation and increased sediment production (Wilson, 1999). Minimizing rill formation is important as rill erosion has been shown to account for approximately 80% of post-fire sediment production (Moody and Martin, 2001; J. Pietraszek, Colorado State University, pers. comm., 2004).

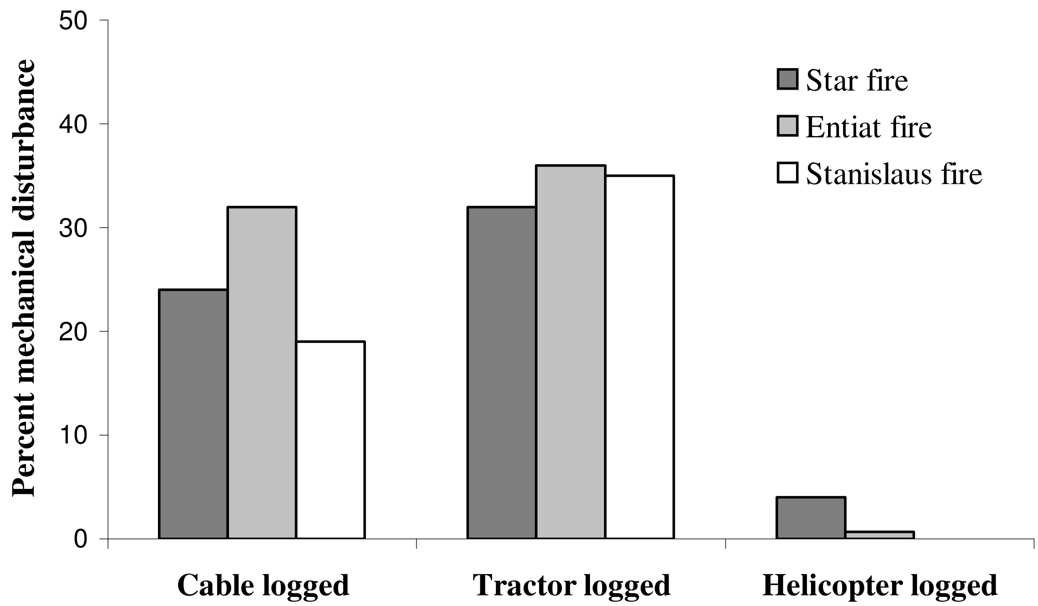

Figure 18. Percent mechanical disturbance by logging treatment for the Star fire, the Entiat fire, and the Stanislaus fire.

In the Star fire water bars were installed on skid trails and cable rows to minimize concentrated flow and rilling. However, some of these water bars failed or were improperly installed, which led to increased rilling and sediment production. The placement of skid trails and cable rows perpendicular to a slope and the proper installation and maintenance of water bars is necessary to minimize sediment production from salvage logging.

There was a significant relationship between the amount of disturbance and sediment production for the cable-logged sites. Cable rows were generally parallel to the slope and, often compacted, and this likely explains why the rill density in the cable-logged sites was more than twice the rill density in the helicopter- and tractor-logged sites. Klock (1975) showed that full suspension during cable logging decreased the amount of soil disturbance on burned sites from 32% to 2.8%. Therefore, cable logging with full suspension should be used on steep slopes to decrease soil disturbance and rill formation.

Tractor logging decreased the amount of litter cover, which led to increased bare soil in summer 2002 and summer 2003. Sediment production rates increase with increasing bare soil, indicating the need to minimize disturbance. The tractor logging also resulted in compacted skid trails, and rills formed when the skid trails were parallel to the slope and not adequately water barred. Decreasing skid trail density on tractor-logged sites and orienting skid trails perpendicular to slopes should help to minimize sediment production.

Another problem with compaction on skid trails and cable rows is the decrease in plant growth and productivity due to loss of soil porosity (SNEP, 1996b). Field observations indicated less vegetative regrowth on skid trails and cable rows than on undisturbed areas, and this can explain the correlation between ground disturbance and percent bare soil in summer 2003.

6.2. Sediment production

Sediment production rates were more variable between sites and years than between logging treatments. The mean sediment production rate from the burned sites in the first wet season was approximately 25 times greater than the mean sediment production rate in the second wet season. The much lower sediment production rates in the second wet season are due primarily to the 96% decrease in rainfall erosivity, as the mean percent bare soil only decreased from 37% to 27%. The variability in sediment production rates between sites within each treatment was quite large. In the first wet season, the coefficient of variation was 0.93 from cable-logged sites, 0.54 from helicopter-logged sites, and 0.70 from tractor-logged sites. Coefficients of variation increased in the second wet season to 1.18 for cable-logged sites, 0.88 for helicopter-logged sites, and 1.52 for tractor-logged sites.

Comparisons indicate that the burned and unlogged sites on the Star fire generally produced less sediment than comparable sites from other studies, while sediment production rates from the burned and logged sites on the Star fire were generally higher than other reported values. In the first wet season on the Star fire (second year after the fire), the mean sediment production rate from the three burned and unlogged sites was 0.4 Mg ha^{-1}. This is only 26% of the second-year sediment production rate from three unlogged high severity sites on the Pendola fire in the nearby Tahoe National Forest (MacDonald et al., 2004). This is somewhat surprising because the erosivity at the Pendola fire sites was approximately 25% less than at the Star fire. The higher sediment production rates on the Pendola fire may be attributed to the higher mean percent bare soil on the Pendola sites (54%) as compared to the Star fire (37%).

On the Entiat fire in Washington, the burned and unlogged watershed produced twice as much sediment as the logged watersheds during the first two years after burning (Helvey, 1980). The mean sediment production rate of 2.6 Mg ha^{-1} from the burned and logged sites on the Star fire in the first wet season was 25% to 45% greater than the second-year values for burned and logged sites on the Entiat fire. Both sites had nearly identical amounts of vegetative cover so the higher sediment production rate on the Star fire may be due to the differences in scale. The Entiat study measured sediment production at the watershed scale, while this study measured sediment production at the hillslope scale. Since sediment production rates generally decrease with increasing scale (Benavides-Solorio, 2003), the difference in spatial scale may explain this small difference in sediment production rates.

On the Stanislaus fire in the central Sierra Nevada, the unlogged sites had a higher mean sediment production rate over a three-year period than the cable- and tractor-logged sites, but these differences were not significant (Chou et al., 1994a). A comparison of sediment production rates for individual years was not possible because the authors simply surveyed total sediment accumulations at the end of the study period (Chou et al., 1994a). However, sediment production rates for the Star fire can be calculated for the first wet season after burning using the complete model in Table 9 and average values for each of the parameters as measured in summer 2002. By adding the calculated first-year sediment production values to the measured values from the second- and third-year after burning, the total sediment production would be approximately 7 Mg ha^{-1} from cable-logged sites and 3.5 Mg ha^{-1} from tractor-logged sites. These values are approximately 75% more than the three-year totals for tractor- and cable-logged sites on the Stanislaus fire (Chou et al., 1994a). Since the two studies had similar amounts of bare soil and ground disturbance, the greater sediment production rates on the Star fire are most likely due to the combination of higher rainfall erosivity and logging disturbance patterns that induced concentrated flow pathways.

The results of these different studies show that post-fire salvage logging can increase or decrease sediment production compared to burned and unlogged sites. To explain these varying results it is necessary to understand the various factors that are controlling sediment production.

6.3. Controls on sediment production

In the first wet season, percent bare soil was the most important control on post-fire sediment production from the burned and logged sites. Figure 16 shows a substantial increase in sediment production as percent bare soil increases from about 18% to 28%. This "threshold" for increasing sediment production is lower than the value of approximately 30% identified for burned but unlogged areas in the Colorado Front Range (Benavides-Solorio, 2003; Libohova, 2004). A study in the central Texas Plateau also indicated that percent bare soil must be greater than 30% to increase post-fire erosion (Wright et al., 1982). The similarity of these values from areas with different amounts and types of precipitation suggests that the percent bare soil needed to induce high erosion rates may be relatively independent of the precipitation regime. Of course, if there is no precipitation there will be no erosion.

Several studies have identified the first two rainy seasons as the critical period for runoff and erosion after wildfires (Inbar et al., 1998; Robichaud et al., 2000; Benevides-Solorio and MacDonald, 2005), and one would expect the same to be true for wildfire plus salvage logging. For the Star fire there were no significant differences in sediment production rates between the second and third wet seasons after burning when sediment production rates were normalized by the annual erosivity. This indicates that the critical period for sediment production after wildfire plus salvage logging can extend beyond the first two wet seasons.

The extension of this critical period on the Star fire is most likely due to the disturbance induced by salvage logging. Skid trails and cable rows parallel to a slope often served as concentrated flow pathways that led to rill formation. These rills may sustain high sediment production rates for several years after a fire by continuing to incise during larger storm events. The salvage logging also increased the amount of bare soil, which was the most important control on post-fire sediment production. The vegetative regrowth in both burned and disturbed areas means that sediment production rates--when normalized by erosivity--should have decreased between the last year of this study and the 2004-2005 wet season, but field measurements ceased in summer 2004 so there are no sediment production data from the fourth wet season after the fire.

It might be possible to reduce the length of the critical period for sediment production by applying post-fire rehabilitation techniques such as mulching. Mulching has been shown to reduce post-fire sediment production rates by 88% to 94% compared to unmulched sites (Bautista et al., 1996; Wagenbrenner et al., in press). Mulching may be most beneficially applied to those areas where skid trails and cable rows are parallel to the slope. Rainfall simulations indicate that needlecast <1 cm thick on 50% of the soil surface can reduce rill erosion by almost 40% (Pannkuk and Robichaud, 2003), and rills are the dominant source of sediment after high-severity wildfire (Moody and Martin, 2001; J. Pietraszek, Colorado State University, pers. comm., 2004).

The results suggest that soil water repellency was not an important factor in the continued extension of the critical period for sediment production. CST values were not significantly different from background levels by the second summer (22 months) after burning. Other studies indicate that soil water repellency may persist for as little as six months (DeByle, 1973; Huffman et al., 2001; MacDonald and Huffman, 2004). The relatively rapid decrease in soil water repellency should reduce sediment production rates over time, as the empirical models developed in this study indicate that soil water repellency at the soil surface is significantly correlated with sediment production. Other studies have yielded similar results (Benavides-Solorio and MacDonald, 2001; DeBano 2002; Benavides-Solorio, 2003).

No CST data are available from immediately after the fire, so it was not possible to assess the initial strength of soil water repellency or the changes in CST values with depth within the first 11 months after burning. It is reasonable to assume that the initial soil water repellency would have been stronger than the values measured in summer 2002 (DeByle, 1973; Huffman et al., 2001; MacDonald and Huffman, 2004), and soil water repellency could have been a more important control on sediment production rates in the 2001-2002 wet season than the first wet season of this study (2002-2003). Additional studies are needed to assess the initial strength and variability of post-fire soil water repellency in the Sierra Nevada.

6.4. Modeling sediment production

The empirical models developed in this study (Table 9) can help land managers predict post-fire erosion from logged and unlogged areas at the hillslope scale. The most useful model for land managers may be the 3-parameter model, as this only requires contributing area, percent bare soil, and annual erosivity. Contributing area can be obtained from maps, digital elevation models, or field measurements, and values for mean annual erosivity can be obtained from maps (e.g., Renard et al., 1997). Percent bare soil can be easily measured in the field with linear transects or plots. The more complete empirical models may be more useful for researchers who have the time to collect spatially-explicit data on soil particle-size distributions and soil water repellency using the critical surface tension approach.

The sediment production models did not included percent disturbance, slope, percent woody debris on the ground surface, or logging treatment. In this study and on the Stanislaus fire, sediment production from the cable-logged sites was significantly correlated with percent ground disturbance (Chou et al., 1994a, b). The significant correlation for cable-logged sites may be due to the relative consistency in the type and pattern of disturbance. Cable logging generally requires that logs be pulled upslope, which creates a pattern of cable rows on each site that are nearly parallel to the slope (Figure 4). On the Star fire, cable rows tended to serve as conduits for concentrated flow that in turn created rills and most likely increased sediment production.

In contrast, tractor logging did not create a consistent pattern of disturbance parallel to the slope (Figures 3 and 4). In some cases sediment moving downslope was trapped in the disturbed areas, while in other cases the skid trails helped concentrate flow and increase sediment production. These differences meant that the amount of disturbance could not be directly linked to sediment production, and this is partly why the effects of salvage logging continue to be controversial. Disturbance on helicopter-logged sites was minimal, had inconsistent patterns, and did not appear to increase or decrease sediment production. The different disturbance patterns among the three logging treatments help explain why percent disturbance was not a significant predictor of sediment production for all of the burned and logged sites, the tractor-logged sites, or the helicopter-logged sites.

Many erosion prediction models include slope, and erosion generally increases rapidly with increasing slope steepness (Renard et al., 1997). However, the increase in erosion with increasing slope may level off once slopes exceed 30% (Wu and Wang, 2001). On the Star fire, 56% of the burned sites had slopes greater than 30%, while only 5% had slopes less than 20%, and the limited range of slopes may explain why slope was not a significant predictor. Future studies should encompass a wider range of slopes in order to more clearly define the effect of slope on post-fire sediment production rates.

Leaving woody debris onsite is sometimes used as a management technique to increase cover, stop downslope sediment movement, and reduce sediment production (Poff, 1989; Shakesby et al., 1996). On average, the burned and logged sites in the Star fire had twice as much ground cover from woody debris than the unburned sites (23% versus 11%). Field observations indicate that woody debris can act as small check dams to trap sediment on the hillslope, but in most cases the woody debris did not have continuous soil contact, and this limited the ability of the woody debris to trap sediment. Hence, the amount of woody debris did not significantly affect sediment production, but the amount of woody debris is another factor that contributes to the observed variability in sediment production rates after salvage logging.

Logging treatment was not a significant variable for predicting post-fire sediment production rates. This suggests that the predictive models developed in this study can be used to estimate sediment production rates after wildfires in the central Sierra Nevada regardless of whether salvage logging was undertaken. An important caveat is that the empirical models in Table 9 should only be applied to areas with similar site conditions. These conditions include hillslopes in the mixed conifer forests of the central Sierra Nevada that have sandy loam soils, a slope range of approximately 15% to 50%, and that have been burned at high severity.

7. CONCLUSIONS

The Star fire burned over 7000 ha in late summer 2001 in the central Sierra Nevada of California. The primary objective of this study was to compare site conditions and hillslope-scale sediment production rates from three post-fire logging treatments, burned but unlogged areas, and unburned areas over the 2002-2003 and 2003-2004 winter wet seasons. Sediment production rates were negligible from the unburned sites, but varied greatly among the burned sites and between years. In the first wet season, the mean sediment production rate for cable-logged sites was twice that of tractor- and helicopter-logged sites. These differences were not significant due to the variability in sediment production between sites.

Mean sediment production rates in the second wet season were only about 4% of the value from the first wet season, as rainfall erosivity was approximately 4% of the value from the first wet season. When sediment production was normalized by erosivity there was no significant difference in sediment production between years. The lack of a significant decline in sediment production indicates that the critical period for sediment production after wildfire plus salvage logging extends through the third wet season after burning.

The data suggest that wildfire plus salvage logging increases sediment production rates compared to burned and unlogged sites. However, the small number of burned and unlogged sites and the high variability in sediment production rates between sites makes it very difficult to separate post-fire sediment production from the additional sediment that might be generated by salvage logging. Future studies must identify and maintain a sufficient number of burned and unlogged sites to better quantify the effects of salvage logging on sediment production.

Simple linear regression showed that percent bare soil was the most important factor controlling sediment production from burned and logged sites in the first wet season (R^2=0.41; p=0.002). Percent bare soil was significantly correlated with the amount of ground disturbance for the burned and logged sites in summer 2002 and summer 2003.

These results suggest that the pattern of ground disturbance is an important factor in determining whether salvage logging will increase or decrease sediment production. Cable rows and skid trails perpendicular to the slope tended to reduce sediment production by acting like sediment traps, while cable rows and skid trails parallel to the slope tended to concentrate flow, induce rill formation, and increase sediment production. Proper installation and maintenance of water bars on skid trails and cable rows should help minimize the increase in sediment production due to salvage logging. The effects of different disturbance patterns on sediment production warrant further study, as this study measured disturbance and rilling, but did not collect spatially-explicit data on disturbance patterns.

Soil water repellency in both the burned and unburned areas was strongest at the soil surface and declined in strength with increasing depth. By two years after burning, there was no significant difference in soil water repellency between burned and unburned locations. Burned areas disturbed by cable or tractor logging had significantly less soil water repellency than undisturbed burned areas. The potential reductions in sediment production due to this decrease in soil water repellency in disturbed areas may be offset by the accompanying increases in percent bare soil, percentage area disturbed, and rilling.

An empirical, multivariate model was developed to predict sediment production using six independent variables: contributing area, percent bare soil, percent litter <1 cm thick, rainfall erosivity, soil water repellency at 0 cm, and D_{50}. This had an overall R^2 of 0.76. A simpler 3-parameter model had an R^2 of 0.64, and this may be more useful for land managers because it only requires contributing area, percent bare soil, and rainfall erosivity. Both models had a slight tendency to over-predict low sediment production values and under-predict high values.

The results indicate that sediment production from salvage logging can be reduced by treatments that minimize percent bare soil and ground disturbance. These include cable logging with full suspension, helicopter logging, or tractor logging with a low density of skid trails. It also is important that any disturbance is oriented perpendicular to the slope in order to minimize concentrated flow pathways that can create rills and increase sediment production. Given the high variability of sediment production rates between sites, the complexity of the various controlling factors, and the paucity of studies on salvage logging, additional research is needed to validate the results from the Star fire and improve our understanding of the effects of post-fire logging on sediment production.

8. LITERATURE CITED

Agee, J.K., 1996. Fire in the Blue Mountains: a history, ecology, and research agenda. In *Search for a Solution: Sustaining the Land, People, and Economy of the Blue Mountains,* R.G. Jaindl, and T.M. Quigley (eds.), American Forests, Washington, D.C., pp. 119-141.

Agee, J.K., 1993. Fire ecology of Pacific Northwest forests. Island Press, Washington, D.C., 493 pp.

Amacher, M.C. and K.P. O'Neill, 2004. Assessing soil compaction on forest inventory and analysis phase 3 field plots using a pocket penetrometer. USDA Forest Service Res. Pap. RMRS-RP-46WWW, Rocky Mountain Research Station, Fort Collins, CO, 10 pp.

Amorocho, J. and B. Wu, 1977. Mathematical models for the simulation of cyclonic storm sequences and precipitation fields. *Journal of Hydrology* 32: 329-345.

Bautista, S., J. Bellot, and V.R. Vallejo, 1996. Mulching treatment for postfire soil conservation in a semiarid ecosystem. *Arid Soil Research and Rehabilitation* 10: 235-242.

Benavides-Solorio, J. and L.H. MacDonald, 2005. Measurement and prediction of post-fire erosion at the hillslope scale, Colorado Front Range. *International Journal of Wildland Fire* 14:1-18.

Benavides-Solorio, J., 2003. Post-fire runoff and erosion at the plot and hillslope scale, Colorado Front Range. Ph.D. Dissertation, Colorado State University, Fort Collins, CO.

Benavides-Solorio, J., and L.H. MacDonald, 2001. Post-fire runoff and erosion from simulated rainfall on small plots, Colorado Front Range. *Hydrological Processes* 15: 2931-2952.

Ben-Dor, E., and A. Banin, 1989. Determination of organic matter content in arid-zone soils using a simple "loss-on-ignition" method. *Communications in Soil Science and Plant Analysis* 20: 1675–1695.

Beschta, R.L., J.J. Rhodes, J.B. Kauffman, R.E. Gresswell, G.W. Minshall, J.R. Karr, D.A. Perry, F.R. Haeur, and C.A. Frissell, 2004. Postfire management on forested public lands of the western United States. *Conservation Biology* 18: 957-967.

Blake, G.R., and K.H. Hartge, 1986. Bulk density. In *Methods of Soil Analysis: Part 1,* A. Klute (ed.), American Society of Agronomy, Madison, WI, pp. 363-375.

Brown, L.C., and G.R. Foster, 1987. Storm erosivity using idealized intensity distributions. *Transactions of the American Society of Agricultural Engineers* 30 (2): 293-307.

Buchanan, T.J., and W.P. Somers, 1969. Discharge measurements at gaging stations. USGS Techniques of Water Resources Investigations, book 3, Ch. A7, Washington D.C., 28 pp.

Bunte, K., and S.R. Apt, 2001. Sampling surface and subsurface particle-size distributions in wadable gravel- and cobble-bed streams for analyses in sediment transport, hydraulics, and streambed monitoring. USDA Forest Service Gen. Tech. Rep. RMRS-74, Rocky Mountain Research Station, Fort Collins, CO, 428 pp.

Campbell, G.S., J.D. Jungbauer, K.L. Bristow, and R.D. Hungerford, 1977. Wildfire effects on a ponderosa pine ecosystem: an Arizona case study. USDA Forest Service Res. Pap. RM-191, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO, 12 pp.

CDF, 2002. California forest practice rules: *Title 14, California code of regulations, chapters 4, 4.5 and 10*. California Department of Forestry and Fire Protection, Sacramento, CA. 212 pp.

Chou, Y.H., S.G. Conard, and P.M. Wohlgemuth, 1994a. Analysis of post-fire salvage logging, watershed characteristics, and sedimentation in the Stanislaus National Forest. In *Proceedings of ESRI Users Conference*. Environmental Systems Research Institute, Redlands, CA, pp. 492-499.

Chou, Y.H., S.G. Conard, and P.M. Wohlgemuth, 1994b. Post-fire salvage logging variables and basin characteristics related to sedimentation, Stanislaus National Forest, California. In *Proceedings GIS '94 Symposium*. Reid, Collins, and Asssociates, Vancouver, Canada, pp. 873-878.

Cooley, K.R., C.L. Hanson, and C.W. Johnson, 1988. Precipitation erosivity index estimates in cold climates. *Transactions of the American Society of Agricultural Engineers* 13: 1445-1450.

DeBano, L.F., 2000. The role of fire and soil heating on water repellency in wildland environments: a review. *Journal of Hydrology* 231-232: 195-206.

DeBano, L.F., D.G. Neary, and P.F. Ffolliott, 1998. Fire's effects on ecosystems. John Wiley and Sons, New York, NY, 333 pp.

DeBano, L.F., 1981. Water repellent soils: a state-of-the-art. USDA Forest Service Gen. Tech. Rep. PSW-46, Pacific Southwest Forest and Range Experiment Station, Berkeley, CA, 21 pp.

DeByle, N.V., 1973. Broadcast burning of logging residues and the water repellency of soils. *Northwest Science* 47: 77-87.

Evens, R., 1980. Mechanics of water erosion and their spatial and temporal controls: an empirical viewpoint. In *Soil Erosion*, Kirkby M.J. and Morgan, P.C. (eds.), John Wiley and Sons, New York, NY, pp. 109-128.

Gardner, W.H., 1986. Water content. In *Methods of Soil Analysis: Part 1,* A. Klute (ed.), American Society of Agronomy, Madison, WI, pp. 493-507.

Grender, G.C., 1961. Note on measurement of grain size in phi units. *Journal of Sedimentary Research* 31 (4): 608.

Helvey, J.D., 1980. Effects of a north-central Washington wildfire on runoff and sediment production. *Water Resources Bulletin* 16: 627-634.

Hudson, N.W., 1993. Field measurements of soil erosion and runoff. *Food and Agriculture Organization of the United Nations Bulletin* 68, 139 pp.

Huffman, E.L., L.H. MacDonald, and J.D. Stednick, 2001. Strength and persistence of fire-induced soil hydrophobicity under ponderosa and lodgepole pine, Colorado Front Range. *Hydrological Processes* 15: 2877-2892.

Ice, G.G., D.G. Neary, and P.W. Adams, 2004. Effects of wildfire on soils and watershed processes. *Journal of Forestry* 106 (2): 16-20.

Inbar, N., M. Tamir, and L. Wittenberg, 1998. Runoff and erosion processes after a forest fire in Mount Carmel, a Mediterranean area. *Geomorphology* 24: 17-33.

Klock, G.O., 1975. Impact of five post-fire salvage logging systems on soils and vegetation. *Journal of Soil and Water Conservation* 30: 78-81.

Libohova, Z., 2004. Effects of thinning and a wildfire on sediment production rates, channel morphology, and water quality in the upper South Platte River watershed. M.S. Thesis, Colorado State University, Fort Collins, CO.

MacDonald, L.H., D.B. Coe, and S.E. Litschert, 2004. Assessing cumulative watershed effects in the central Sierra Nevada: Hillslope measurements and catchment-scale modeling. In *Proceedings of the Sierra Nevada Science*

Symposium, October 7-10, 2002. USDA Forest Service, Gen. Tech. Rep. PSW-GTR-193. Pacific Southwest Research Station, Albany, CA, pp. 149-157.

MacDonald, L.H., and E.L. Huffman, 2004. Post-fire soil water repellency: persistence and soil moisture thresholds. *Soil Science Society of America Journal* 68:1729-1734.

Mackay, S.M., and P.M. Cornish, 1982. Effects of wildfire and logging on the hydrology of small catchments near Eden, N.S.W. In *Proceedings of 1st National Symposium on Forest Hydrology*. Australian Foreign Council, pp. 111–117.

McIver, J.D., and L. Starr, 2001. A literature review on the environmental effects of post-fire logging. *Western Journal of American Forestry* 16: 159-168.

McIver, J.D., and L. Starr (tech. eds.), 2000. Environmental effects of post-fire logging: Literature review and annotated bibliography. USDA Forest Service Gen. Tech. Rep. PNW-GTR-486, Pacific Northwest Research Station, Portland, OR, 72 pp.

Moody, J.A., and D.A. Martin, 2001. Initial hydrologic and geomorphic response following a wildfire in the Colorado Front Range. *Earth Surface Processes and Landforms* 26: 1049-1070.

Mongomery, D.R., and W.E. Dietrich, 1994. Landscape dissection and drainage area-slope thresholds. In *Theory in Geomorphology*, M.J. Kirby (ed.), John Wiley and Sons, New York, NY, pp. 221-246.

Mutchler, C.K., C.E. Murphree, and K.C. McGregor, 1994. Laboratory and field plots for erosion research. In *Soil Erosion Research Methods*, R. Lal (ed.), St. Lucie Press, Delray Beach, FL, pp. 11-38.

Ott, R.L., and M. Longnecker, 2001. An introduction to statistical methods and data analysis. Duxbury, Pacific Grove, CA, 1152 pp.

Pannkuk, C.D., and P.R. Robichaud, 2003. Effectiveness of needle cast at reducing erosion after forest fires. *Water Resources Research* 39 (12): 1-9.

Parker, K.W., 1951. A method for measuring trend in range condition on national forest ranges. Administrative report, USDA Forest Service, Washington, D.C., 26 pp.

Poff, R., 2002. Existing soil quality conditions on the Star fire: Eldorado National Forest. Nevada City, CA, 36 pp.

Poff, R., 1989. Compatibility of timber salvage operations with watershed values. In *Proceedings of Symposium on Fire and Watershed Management*. USDA Forest Service, Gen. Tech. Rep. PSW-109, Pacific Southwest Forest and Range Experiment Station, Albany, CA, pp. 137-140.

Renard, K.G., G.R. Foster, G.A. Weesies, D.K. McCool, and D.C. Yoder, 1997. Predicting soil erosion by water-a guide to conservation planning with the Revised Soil Loss Equation (RUSLE). USDA Agricultural Handbook No. 703, 404 pp.

Rinne, J.N., 1996. Short-term effects of wildfire on fishes and aquatic macroinvertebrate in the southwestern United States. *North American Journal of Fisheries Management* 16: 653-658.

Robichaud, P.R., and R.E. Brown, 2002. Silt fences: An economical technique for measuring hillslope soil erosion. USDA Forest Service Gen. Tech. Rep. RMRS-GTR-94, Rocky Mountain Research Station, Fort Collins, CO, 24 pp.

Robichaud, P.R., J. L. Beyers, and D.G. Neary, 2000. Evaluating the effectiveness of post-fire rehabilitation treatments. USDA Forest Service Gen. Tech. Rep. RMRS-GTR-63, Rocky Mountain Research Station, Fort Collins, CO, 85 pp.

Robichaud, P.R., 2000. Forest fire effects on hillslope erosion: What we know. *Watershed Management Council Networker* 9 (1), Winter 2000.

Robichaud P.R., and Waldrop T.A., 1994. A comparison of surface runoff and sediment production rates from low-and-high severity site preparation burns. *Water Resources Bulletin* 30: 27-34.

Shakesby, R.A., D.J. Boakes, C.D.O.A. Coelho, A.J.B. Gonclaves, and R.P.D. Walsh, 1996. Limiting the soil degradational impacts of wildfire in pine and eucalyptus forests in Portugal: a comparison of alternative post-fire management practices. *Applied Geography* 16: 337–355.

Simons, D.B., and F. Sentürk, 1992. Sediment transport technology-water and sediment dynamics. Water Resources Publications, Littleton, CO, 919 pp.

Sirvent, J., G. Desir, M. Gutierrez, C. Sancho, and G. Benito, 1997. Erosion rates in badland areas recorded by collectors, erosion pins, and profilometer techniques (Ebro Basin, NE-Spain). *Geomorphology* 18: 61-75.

SNEP, 1996a. Sierra Nevada Ecosystem Project: *Assessment summaries and management strategies.* Vol. I, Center for Water and Wildland Resources, University of California, Davis. 210 pp.

SNEP, 1996b. Sierra Nevada Ecosystem Project: *Assessment and scientific basis for management options.* Vol. II, Center for Water and Wildland Resources, University of California, Davis. 1531 pp.

USDA Forest Service, 2002. Final environmental impact statement, Star fire restoration. Eldorado National Forest, Placerville, CA, 241 pp.

USDA Forest Service, 1995. Burned-area emergency rehabilitation handbook. Forest Service Handbook 2509.13-95-7. Washington, D.C., Chapter 10, 18 pp.

USDA Forest Service, 1985. Soil survey of the Eldorado National Forest, California. Pacific Southwest Region, Placerville, CA, 216 pp.

Wagenbrenner, J.W., L.H. MacDonald, and D. Rough, in press. Effectiveness of three post-fire rehabilitation treatments in the Colorado Front Range.

Wagenbrenner, J. W., 2003. Effectiveness of burned area emergency rehabilitation treatments, Colorado Front Range. M.S. Thesis, Colorado State University, Fort Collins, CO.

Wallis, M.G., and D.J. Horne, 1992. Soil water repellency. In *Advances in Soil Science,* B.A. Stewart (ed.), Vol. 20, Springer Verlag, New York, NY, pp. 91-146.

Watson C.L., and J. Letey, 1970. Indicies for characterizing soil-water repellency based upon contact angle-surface tension relationships. *Soil Science Society of America Proceedings* 34: 841-844.

Wells, C.G., R.E. Campbell, L.F. DeBano, C.E. Lewis, R.L. Fredriksen, E.C. Franklin, R.C. Froelich, and P.H. Dunn, 1979. Effects of fire on soil: a state-of-knowledge review. USDA Forest Service Gen. Tech. Rep. WO-7, Washington, DC, 34 pp.

Wilson, C.J., 1999. Effects of logging and fire on runoff and erosion on highly erodible granitic soils in Tasmania. *Water Resources Research* 35: 3531-3546.

Wright, H.A., F.M. Churchill, and J.A. Jones, 1982. Soil loss, runoff and water quality of seeded and unseeded steep watersheds following prescribed burning. *Journal of Range Management* 35: 382-385.

Wu, C.C., and A.B. Wang, 2001. Effect of slope steepness on soil loss for steep slopes. In *Soil Erosion Research for the 21st Century, Proceedings of the International Symposium.* American Society of Agricultural Engineers, St. Joseph, MI, pp. 20-23.